FINAL REPORT

Detailed Field Investigation of Vapor Intrusion Processes

ESTCP Project ER-0423

September 2008

Thomas E. McHugh, Ph D.
GSI Environmental, Inc.

Tim N. Nickels
GSI Environmental, Inc.

Environmental Security Technology
Certification Program

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 SEP 2008**	2. REPORT TYPE **Final**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Detailed Field Investigation of Vapor Intrusion Processes**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Thomas E. McHugh, Ph D. Tim N. Nickels**		5d. PROJECT NUMBER **ER-0423** 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **GSI Environmental, Inc. 2211 Norfolk, Suite 1000 Houston, TX 77098-4044**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program 901 North Stuart Street, Suite 303 Arlington, VA 22203**		10. SPONSOR/MONITOR'S ACRONYM(S) **ESTCP** 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**338**	

Table of Contents Page

Table of Contents Page

Table of Contents Page

Table of Contents Page

List of Tables

Table of Contents Page

List of Figures

List of Acronyms

List of Acronyms

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
API	American Petroleum Institute
BTEX	benzene, toluene, Ethylbenzene, and xylenes
bgs	below ground surface
COC	chemical of concern
CSM	conceptual site model
1,1-DCE	1,1-dichloroethene
DoD	Department of Defense
DQO	data quality objective
ECD	electron capture detector
EPA	Environmental Protection Agency
ESTCP	Environmental Strategic Technology Certification Program
FID	flame ionization detector
GC	gas chromatography
GC/MS	gas chromatography/mass spectrometry
HVAC	heating, ventilation, air conditioning
LCS	laboratory control standard
MCL	maximum concentration level
MDL	method detection limit
MQL	method quantitation limit
MS/MSD	matrix spike/matrix spike duplicate
MTBE	methyl tertiary-butyl ether
NAPL	non-aqueous phase liquid
NELAP	National Environmental Laboratory Accreditation Program
O&M	operation and maintenance
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste Emergency Response
Ppbv	parts per billion by volume
PCE	tetrachloroethene (also called perchloroethene)
PID	photoionization detector
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RBCA	risk-based corrective action
RCRA	Resource Conservation and Recovery Act
RL	reporting limit
RPD	relative percent difference
SF_6	sulfur hexafluoride
SIM	selective ion monitoring
SOP	standard operating procedure
SVOC	semivolatile organic compound
TCA	trichloroethane

List of Acronyms

TCE	trichloroethene
TCEQ	Texas Commission on Environmental Quality
TPH	total petroleum hydrocarbons
VI	vapor intrusion
VOC	volatile organic compound

Acknowledgements

This project would not have been possible without the support and contribution of numerous individuals and organizations. The authors thank Ivette O'Brien and Samuel Brock of Air Force Center for Environmental Excellence (AFCEE) for support and oversight; Kyle Gorder, Art Whallon, Charles Butchee, and other personnel at Hill Air Force Base (AFB) and Altus AFB for providing access and facilitating implementation of the project at these bases; Blayne Hartman and the staff of H&P Mobile Geochemistry for project support; Doug Hammond of the University of Southern California for analysis of radon concentrations in air and soil gas samples; Chet Clarke of the Texas Commission on Environmental Quality (TCEQ) for review and comment on the project plan; the ESTCP technical review staff for helpful technical comments and suggestions; and Andrea Leeson and the Environmental Strategic Technology Certification Program (ESTCP) program staff at Hydrogeologic for invaluable project support.

Executive Summary

Demonstration Objectives

The primary objective of this demonstration study was to identify a cost effective and accurate protocol for investigation of vapor intrusion into buildings overlying contaminated groundwater. Performance objectives are summarized in Table E.1.

Table E.1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	1) Collection of data representative of site conditions.	Precision, Accuracy, Completeness, Representativeness, and Comparability as defined in Table 4.2.1 and Appendix B.	Objective Attained (See Section 4.3)
Quantitative	2) Vapor Intrusion Impact at Demonstration Site	Indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources.	Objective Attained (See Section 4.4.1)
Qualitative	3) Reliable Vapor Intrusion Investigation Approach	Accuracy of vapor intrusion determination as characterized by false positive and false negative rates. Identify limited scope investigation approach with higher accuracy than current approaches such as USEPA 2002.	Objective Attained (See Section 4.6)

Intensively monitored sites, such as the Borden Landfill in Canada, have greatly contributed to our understanding of the physical and chemical processes that control the transport of chemicals in groundwater. For this project, we have used a similar approach (i.e., intensively monitored sites with specially-designed monitoring networks) to address the critical groundwater-to-indoor-air vapor intrusion pathway. The performance objectives were met by:

1) Collecting a high density of data related to vapor intrusion at the test sites,
2) Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test sites, and
3) Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

Regulatory Drivers

At a limited number of sites in the U.S., migration of volatile organic compounds (VOC) from affected groundwater via vapor phase diffusion has impacted indoor air quality in overlying structures, posing a potentially significant, yet previously unrecognized human health concern for such properties. To address this concern, the Environmental Protection Agency (EPA) has

issued the "Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils," (EPA 2002), providing conservative screening limit concentrations for various VOC in groundwater. The high level of conservatism in the EPA and state guidance reflects the current limitations of our understanding of the physical and chemical processes that contribute to vapor intrusion. A primary goal of this project has been to support the development of refined vapor intrusion guidance based on an improved understanding of the site-specific factors which influence vapor intrusion.

Overview of Demonstration

For this demonstration, vapor intrusion site investigations have been completed at a total of three buildings located at two demonstrations sites: two single-family residences near Hill AFB and a small office building at Altus AFB. For each site, the investigation program consisted of an initial sample point installation and sampling event and one (Hill AFB) or two (Altus AFB) follow-up sampling events. The sampling program, illustrated in Figure E.1, was designed to yield a high density of data around each of the demonstration buildings.

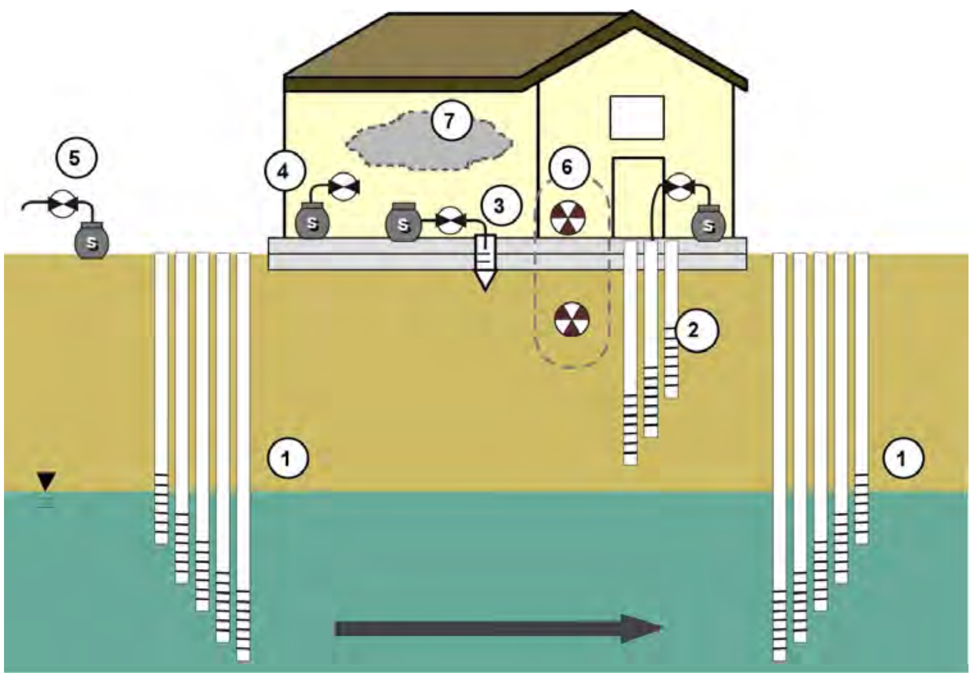


Figure E.1 Conceptual Data Collection Plan for Detailed Evaluation of the Vapor Intrusion Pathway: 1) Multi-level Discrete Depth Samples Upgradient, Midgradient, and Downgradient of the Building Used to Characterize Groundwater Mass Flux (3 multi-level clusters)**; 2) Multi-level Soil Gas Sampling Conducted Below or Adjacent to the Building used to Characterize Soil Gas Concentration Gradients and Mass Flux** (3 multi-level clusters)**; 3) Sub-slab Soil Gas Samples, Combined with the other Data, Provide an Understanding of Transport From the Groundwater Source to Indoor Air** (3 sample points)**; 4) Indoor Air Samples** (3 sample points)**, Combined with 5) Ambient Air Samples** (3 sample points) **and 6) Analysis of Radon Allows Separation of Indoor Air Sources and Vapor Intrusions Sources; 7) Unique Tracer Gas Released Within the Building Allows for Accurate Measurement of Building Air Exchange Rate.**

In order to fully characterize the distribution of VOCs at each site, several sampling events were conducted at each building as summarized in Table E.2.

Table E.2: Summary of Sampling Event by Demonstration Building.

Sample Event	Demonstration Building		
	Altus 418	**Hill Res. #1**	**Hill Res. #2**
Soil Gas Point Purge Study	X	X	X
Initial Sampling Event	X	X	X
Short-Term Follow-up	X		
Longer-Term Follow-up	X (2 events)	X	X
Building Depressurization		X	

This sampling program yielded a large data set suitable for detailed evaluation of vapor intrusion processes.

Summary of Data Quality

The collection of site data representative of actual site conditions was achieved through compliance with the Quality Assurance Project Plan (QAPP), included as Appendix B. The QAPP details the sampling and analysis procedures that were utilized for each type of sample collected during the data collection portion of the project. In addition, the QAPP defines quality assurance objectives for precision, accuracy, completeness, representativeness, and comparability that were used to quantitatively evaluate the quality of the data obtained.

For the purpose of the data usability evaluation, analytical results were evaluated in groups: i) custody procedures, holding time, arrival temperatures, ii) sampling procedures and field instrumentation, iii) precision assessment, iv) accuracy assessment, and v) completeness assessment. A summary data usability evaluation for this project is presented in Table E.3.

Table E.3: Summary of Data Quality Performance.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Performance Criteria for Data Quality Assurance (Quantitative)			
Precision	+/- 30% relative percent difference (RPD)	1 duplicate per 20 samples for all VOC, SF_6, and radon analyses (water and air/gas)	RPD goal met in 82% of duplicate pairs
Accuracy	Field blanks below PQLs. Laboratory accuracy as defined in Appendix B, Tables 2.2 and 2.3	All VOC analyses (water and air/gas)	Goal achieved in 98% of field blanks and laboratory QA/QC samples
Completeness	> 90% valid field samples. >95% valid laboratory results	All VOC analyses (water and air/gas)	Achieved
Performance Criteria for Data Quality Assurance (Qualitative)			
Representativeness	Use of field sampling procedures, laboratory analytical procedures, sample holding times, etc. defined in QAPP	All field samples	Goal achieved for 99% of samples
Comparability	Use of standard and consistent sampling and analysis procedures for all samples, as defined in QAPP	All field samples	Goal achieved for 99% of samples

Over the course of the project, we implemented changes to field procedures to address minor data quality issues identified from previous events. To the extent possible, consistent field procedures were used across sampling events to ensure comparable results were obtained. The resulting project data set was determined to be suitable for evaluation of vapor intrusion in accordance with the defined performance objectives.

Summary of Demonstration Findings

The demonstration data set was evaluated in accordance with the performance criteria defined in the project demonstration plan and summarized in Table E.4.

Table E.4: Summary of Demonstration Performance

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Performance Criteria for Technology Demonstration (Qualitative and Quantitative)			
Vapor Intrusion Impact	Presence or absence of vapor intrusion impact at test site. Vapor intrusion impact defined as indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources	Detection of VOCs in indoor air at concentrations exceeding USEPA, 2002 indoor air screening limits. If limits exceeded, evaluation of sub-slab and indoor air data to separate vapor intrusion from background indoor air sources as described in Section 4.3 of Demonstration Plan	Evaluation of indoor, ambient, and sub-slab VOC and radon concentrations indicated an absence of vapor intrusion impacts above applicable regulatory limits in all three of the demonstration buildings during each of the sampling events. Application of the same investigation approach at other buildings would be expected to yield definitive results concerning the presence or absence of a vapor intrusion impact (see Section 4.4.1)
Movement of VOCs Across Key Interfaces	Calculation of mass flux across key vapor intrusion pathway interfaces, see Section 4.3 of Demonstration Plan	Consistent or decreasing mass flux along the vapor intrusion pathway	Calculated mass flux values had high uncertainty and did not show a consistently decreasing mass flux along the vapor intrusion pathway (See Section 4.4.2)

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Spatial and Temporal Variability in VOC Concentration	Calculation of spatial and temporal variability in chemical concentration for each environmental medium investigated	Statistical measures of variability as described in Section 4.3 of Demonstration Plan	High spatial and longer-term (months) temporal variability in subsurface VOC concentrations compared to above-ground VOC concentrations indicate that a larger number of samples are required to characterize VOC concentrations in subsurface media. Analytical, sample, and short-term (days) temporal variability do not appear to be a major sources of uncertainty in vapor intrusion evaluations (see Section 4.4.3)
Attenuation Factors	Calculation of attenuation factors describing the attenuation of chemicals from various environmental media to indoor air	Statistical measures of variability as described in Section 4.3 of the Demonstration Plan	Calculated attenuation factors had moderate to high uncertainty but were consistently below USEPA default values for pathway screening See Section 4.4.4)
Site Physical Characteristics	Measurement of site soil characteristics and other physical characteristics of the site	Correlation of site characteristics to VOC distributions and fluxes as described in Section 4.3 of the Demonstration Plan	Data set did not show expected correlation between lower soil permeability and higher VOC attenuation (See Section 4.4.5)
Reliable Vapor Intrusion Investigation Approach	Identification of a limited site investigation program that will provide a reliable indication of vapor intrusion impacts	Statistical comparison of accuracy of vapor intrusion impact predicted by limited subset of site data compared to full set of data obtained for the site, as described in Section 4.3 of the Demonstration Plan	We have developed a recommended approach for the reliable investigation of vapor intrusion. (See Section 4.6)

Key project findings are summarized as follows:

Vapor Intrusion Impact: A vapor intrusion impact, defined as an exceedance of applicable indoor air VOC concentration screening values attributable to vapor intrusion, was not observed in any of the demonstration buildings. However, a statistically significant increase in indoor VOC concentration relative to ambient concentrations was observed during some sample events. The analysis of VOC and radon concentrations in ambient air, indoor air, and sub-slab gas samples, provided a data set that could be used to identify the most likely source of VOC detected in indoor air. This analysis indicated that trichloroethene (TCE) in indoor air during the second Altus sampling event at concentrations above EPA screening levels were attributable to ambient sources and not vapor intrusion. The data evaluation indicated some migration of TCE and/or PCE from the subsurface to indoor air at the demonstration buildings during some sample events, however, in all cases the estimated VOC concentration in indoor air attributable to vapor intrusion was below the applicable screening level for the site. The impact of induced building depressurization on vapor intrusion (VI) was evaluated at Hill AFB Residence #1 and the results indicate that this may be a useful tool for the evaluation of vapor intrusion under "worst case" conditions. However, further validation of this approach is needed.

Use of Radon as a Tracer for Soil Gas Movement into Buildings: Based on the difference between indoor and ambient radon concentrations and the absence of indoor sources of radon, radon was determined to be a sensitive tracer for the movement of soil gas through the building foundation. The measured radon attenuation factors have been used to calculate the concentration of VOCs in indoor air attributable to vapor intrusion and to evaluate the possible contribution of indoor VOC sources to measured indoor VOC concentrations. For example, the difference between the measured concentration of TCE indoor air and the estimated concentration attributable to vapor intrusion suggested a likely indoor source of TCE at Altus AFB Building 418 in December 2006 and at Hill AFB Residence #1 in March 2006 (see Table 4.4.1.5).

Radon is a useful tracer for the movement of soil gas because radon is emitted from all soils and is present in all soil gas. However, because VOCs in soil gas originate from specific sources while radon in soil gas originates from all soils, the distribution of radon and VOC may be different within subsurface gas below a building. This difference could result in differences between the measured attenuation factors that are not attributable to indoor sources of VOC. Radon data is likely to be most useful for the evaluation of vapor intrusion when radon and VOC concentrations are measured at multiple sub-slab sample locations allowing for an evaluation of the differences in subsurface distribution of these chemicals.

Movement of VOCs Across Key Interfaces: Mass flux was used to track the movement of VOC across key interfaces along the vapor intrusion pathway. Mass flux through shallow groundwater was consistently higher than mass flux through soil gas or through the building foundation indicating that only a small fraction of the VOC mass diffused from groundwater to soil gas as

the groundwater migrated under the demonstration building. In contrast, no consistent relationship was observed between estimated mass flux through soil gas and through the building foundation.

The large uncertainty in mass flux estimates may limit their utility for evaluation of vapor intrusion. The accuracy of the mass flux estimate is limited by both spatial variability in VOC concentration and uncertainty in site hydrogeologic parameters required for the mass flux calculations. Because the lateral mass flux of VOC through shallow groundwater below a building is typically higher than the vertical mass flux of VOC through the soil column below the building, evaluation of mass flux in shallow groundwater may provide a conservative screening tool for the vapor intrusion pathway when this mass flux is less than would be required to sustain an indoor vapor intrusion impact. However, further validation of the utility of groundwater mass flux for screening of vapor intrusion would be required.

<u>Spatial and Temporal Variability in VOC Concentration</u>: Demonstration results were analyzed to determine the most important sources of variability in VOC concentrations during vapor intrusion investigations. Relative percent difference (RPD) was used to describe variability between paired measurements and coefficient of variation (CV) was used to describe variability in data sets of three or more measurements. Analytical variability was very low with an average RPD between laboratory duplicate measurements of 2.5% and surrogate recoveries typically between 98% and 102%. Field duplicate variability was higher, but acceptable, with 78% of field duplicate VOC measurements (and 82% of all field duplicate measurements) achieving the data quality objective of an RPD<30%. Short-term temporal variability (i.e., time scale of days) was only slightly higher than field duplicate variability with 65% of duplicate VOC measurements showing an RPD<30%. These results indicate the variability on the time scale of days was largely influenced by sample collection and/or very small-scale field variability.

Spatial variability in VOC concentration was evaluated through the CV in VOC concentrations between samples from three spatially-separated sample points. Spatial variability was much higher in subsurface gas samples (i.e., average CV = 0.92 to 0.96 in sub-slab, soil gas, and well headspace samples) compared to indoor (average CV = 0.26) and ambient air samples (average CV = 0.55). Based on this finding, an efficient vapor intrusion investigation program that includes samples from both media should include a larger number of subsurface gas samples than above-ground air samples. Longer-term temporal variability (i.e., time scale of months) in subsurface gas samples was similar to the spatial variability (i.e., average CV = 0.80 to 1.02 in sub-slab, soil gas, and well headspace samples). This finding suggests that subsurface gas sampling should be balanced between spatially separated sample points and temporally separated sample events.

<u>Attenuation Factors</u>: There was significant uncertainty in the calculated subsurface to indoor air attenuation factors, with the standard deviation for the calculated values similar to or greater than the calculated attenuation factor values. Despite this uncertainty, the calculated attenuation factors were consistently less than the EPA default values indicating that the EPA default values

were conservative and protective for the three demonstration buildings evaluated. Measured sub-slab to indoor air attenuation factors ranged from 3.8 x 10^{-4} to 7.6 x 10^{-3} compared to the current EPA default value of 1.0 x 10^{-1} and the proposed value of 5.0 x 10^{-2}. Measured groundwater to indoor air attenuation factors ranged from 2.9 x 10^{-6} to 3.6 x 10^{-4} compared to the current EPA default value of 1.0 x 10^{-3} (the USEPA has not proposed to change this default value).

Typically, attenuation factors are calculated based a single subsurface and a single indoor air measurement. For this project, each attenuation factor was calculated based on a minimum of three subsurface and three indoor air measurements. The high uncertainty associated with these relatively data rich attenuation factors indicates that typical attenuation factors are extremely uncertain and may have limited utility for evaluation of the vapor intrusion pathway.

Site Physical Characteristics: The demonstration yielded a limited data set for the evaluation of site physical characteristics, supporting only a limited evaluation of the impact of site characteristics on vapor intrusion. However, the available data do not support the hypothesis that lower permeability vadose zone soils decrease the potential for vertical migration of VOCs from groundwater through the unsaturated soil column, decreasing the potential for vapor intrusion impacts. At the Hill AFB site, the vadose zone soil permeability was approximately 10x higher at Residence #2 compared to Residence #1 based on both laboratory and field measurements. However, the March 2006 sampling event indicated vertical migration of TCE through the vadose zone soils to the building at Residence #1 but not at Residence #2 despite similar concentration of TCE measured in shallow groundwater at the top of the water table at the two residences. As a result, the groundwater to indoor air attenuation factor at Residence #1 was at least 50x higher than at Residence #2, where non-detect results for TCE in sub-slab samples yielded an upper-bound estimate of the attenuation factor. These results indicate greater VOC attenuation at Residence #2, despite the presence of higher permeability vadose zone soils at this location. (Note that a higher value for the attenuation factor indicates less VOC attenuation).

Recommendations for Investigation of Vapor Intrusion: The results of the demonstration have been used to develop a recommended sample collection program for the evaluation of vapor intrusion in individual buildings, summarized in Table E.5.

Table E.5: Recommended Sample Collection Program for Evaluation of Vapor Intrusion.

Environmental Medium	Analyses	Sample Duration	Sample Container	Number of Samples	Sample Locations
Ambient air	VOCs by TO-15[1]	24 hr	6L Summa	1	Upwind
	Radon[2]	Grab	0.5 L Tedlar	1	
Indoor air	VOCs by TO-15[1]	24 hr	6L Summa	1 - 2[3]	Lowest floor
	Radon[2]	Grab	0.5 L Tedlar	1 - 2[3]	
Sub-slab gas	VOCs by TO-15	Grab	0.4L or 1L Summa	3 - 5[3]	Distributed below lowest floor
	Radon[2]	Grab	0.5 L Tedlar	3 - 5[3]	

** Note: 1) TO-15 SIM may be required for indoor and ambient air samples to achieve detection limits below regulatory screening values. TO-15 analyses are conducted by numerous commercial laboratories. The TO-15 analyte list may vary between laboratories and should be reviewed to ensure inclusion of all volatile COC.*
2) Radon samples analyzed by Dr. Doug Hammond (dhammond@usc.edu) at the University of Southern California Department of Earth Sciences using the extraction method of Berelson, 1987 and the analysis method of Mathieu, 1998.
3) Recommended number of samples for a typical residence with a 1000 - 2000 ft^2 foundation. Additional samples may be appropriate for larger structures.

The results of the investigation program should be used to evaluate vapor intrusion based on a weight-of-evidence approach using the following data evaluation methods:

Indoor Air Data: If indoor VOC concentrations are below indoor screening levels then no further immediate evaluation of vapor intrusion is required. Additional follow-up monitoring may be warranted at some buildings to evaluate the potential for intermittent vapor intrusion impacts to occur at other times.

Evaluation of Potential VOC Sources: If indoor VOC concentrations exceed indoor screening levels, then VOC and radon concentrations should be evaluated to help identify the most likely source or sources of the indoor air impacts.

- *Evidence of Ambient Sources*: Ambient VOC concentrations greater than or similar to indoor VOC concentrations indicate that ambient sources are the likely primary source of VOCs in indoor air.
- *Evidence of Indoor Sources*: Indoor VOC concentrations >10% of below foundation concentrations, and/or large differences in below foundation to indoor air attenuation factors between VOC, indicate that indoor sources are likely the primary source of one or more of the VOC in indoor air. For example, a tetrachloroethene (PCE) attenuation factor of 0.03 and a TCE attenuation factor of 0.001 would suggest a likely indoor source of PCE.
- *Evidence of Vapor Intrusion*: The following factors together indicate that vapor intrusion is likely the primary source of observed indoor air impacts: i) indoor VOC concentrations greater than ambient VOC concentrations, ii) below foundation to indoor air attenuation factors <0.01 and, iii) below foundation to indoor air attenuation factors similar for all VOCs and for radon.

Currently available regulatory guidance does not provide clear and consistent recommendations for the field evaluation of VI at individual buildings. As a result, the current approaches to the investigation of VI vary widely between sites. When comparing investigation results between sites, it is difficult to separate the effects of site characteristics from the effects of differing investigation methods. The application of a consistent field investigation program, such as that recommended here, across buildings and sites will yield comparable data sets that provide an improved understanding of the site-specific factors contributing to the presence or absence of vapor intrusion impacts at individual buildings. Typical costs for the recommended investigation approach are provided in Section 4.6.3 of this report.

Summary of Project Deliverables

The results of this demonstration have been used to generate the following products:

1) Procedural Guidelines for Reliable Evaluation of Vapor Intrusion: A cost-effective and reliable approach for the evaluation of vapor intrusion. Provided as a white paper, "Recommendations for the Investigation of Vapor Intrusion" and also presented in Section 4.6 of this report.
2) Accessible Site Characterization Database: A web-accessible database presenting the data collected for this project. This database provides VOC concentration results as well as other site characteristics such as soil parameters and building characteristics. It provides an empirical dataset for evaluation of predictive vapor intrusion models. In addition, the database allows other interested parties to evaluate spatial and temporal variability of VOC in groundwater, soil gas, sub-slab gas, and indoor air.
3) Technology Transfer: A fact sheet and several peer-reviewed publications present key findings that are likely to be useful to state and federal regulators, and others, responsible for establishing policies related to vapor intrusion.
4) Permanent and Reusable Monitoring Systems: The monitoring networks installed at the two sites selected for this study have been constructed so as to facilitate future resampling and reuse as desired by Department of Defense (DoD). Similar to the Borden Landfill approach, these facilities can be used in future studies to accommodate the continued development and validation of an improved conceptual model and predictive tools for the vapor intrusion pathway.

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

1. Introduction

1.1 Background

Problem: Although the scientific and regulatory communities have been aware of the subsurface-to-indoor air VI pathway for over two decades, most of the early focus regarding this pathway was limited to the migration of radon or landfill gas into indoor air (Altshuler and Burmaster 1997; Richardson 1997; Folkes and Arell 2003). In the early nineties, this pathway drew renewed interest from the regulatory community due to the implementation of risk-based corrective action (RBCA) concepts (ASTM 1994) at corrective action sites, and due to the publication of the Johnson-Ettinger Model (Johnson and Ettinger 1991). The Johnson-Ettinger model extended some of the assumptions employed originally in radon vapor intrusion models to represent diffusive and pressure-driven (i.e., advective) transport of volatile organic compounds (VOC) from a subsurface vapor source to indoor air. In the mid-nineties, several state regulatory agencies and the EPA (EPA 2000) applied the Johnson-Ettinger model, together with conservative assumptions, to develop risk-based groundwater screening levels that would be protective of human exposure to indoor air impacted by VI. In the late 1990s, the groundwater-to-indoor air vapor intrusion pathway received national attention when two Colorado sites with chlorinated solvent groundwater plumes were found to have elevated levels of chlorinated VOC in the indoor air of overlying surface structures (Renner, 2002). Largely in response to the findings at the two Colorado sites, the Corrective Action Branch of the Office of Solid Waste and Emergency Response (OSWER) at the EPA developed and released a draft supplemental guidance in 2001 (EPA 2001) to facilitate the evaluation of VI at RCRA corrective action facilities. In November 2002, the EPA issued the Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils ("EPA Vapor Intrusion Guidance"; (EPA 2002), to extend the evaluation of the VI pathway to Superfund and other corrective action sites (Folkes and Arell 2003). Due to the failure of modeling to identify the vapor intrusion impacts at the Colorado sites, these EPA draft guidance documents have a reduced reliance on models for pathway screening and have increased the requirements for direct measurement to evaluate the potential for vapor intrusion at corrective action sites. In addition, a number of state and local regulatory agencies have recently issued new or updated guidance that similarly emphasizes field measurements over modeling for the evaluation of VI (WDHFS 2003; PaDEP 2004; NJDEP 2006; NYDOH 2006). The EPA and state guidance documents use conservative screening procedures to compensate for a limited understanding of the site-specific parameters that control the VI processes. An improved understanding of these processes at sites with VOC contamination will support the development of improved site investigation approaches and refined regulatory guidance.

Technology Demonstration: Intensively monitored sites, such as the Borden Landfill in Canada, have greatly contributed to our understanding of the physical and chemical processes that control the transport of chemicals in groundwater. For this project, we have used a similar approach

(i.e., intensively monitored sites with specially-designed monitoring networks) to address the critical groundwater-to-indoor-air vapor intrusion pathway. By increasing our understanding of this critical pathway, guidelines can be improved, thereby better focusing efforts and associated cost increases on only those sites where indoor vapor concerns are warranted. Towards this end, this project has focused on validating a streamlined site investigation technology by obtaining a detailed understanding of vapor intrusion processes associated with dissolved chlorinated solvent plumes at Altus Air Force Base (Altus AFB) in Oklahoma and Hill Air Force Base (Hill AFB) in Utah. This technology will reduce site investigation costs associated with vapor intrusion at DoD facilities by reducing the amount of data required to evaluate vapor intrusion and by increasing the accuracy of the evaluation.

1.2 Objectives of the Demonstration

<u>Objectives</u>: The primary objective of this demonstration study was to identify a cost effective and accurate protocol for investigation of VI into buildings overlying contaminated groundwater. This objective was met by:

1) Collecting a high density of data related to vapor intrusion at the test sites,
2) Analyzing this data to obtain a thorough understanding of VI processes at the test sites, and
3) Utilizing the results to develop a reliable and cost-effective approach for the investigation of vapor intrusion at other sites.

In this report, the term "*vapor intrusion impact*" is used to describe the presence of a vapor intrusion condition that requires a response action due to an exceedance of applicable regulatory screening levels. The meaning of the term "*vapor intrusion impact*" is intended to be similar to the terms soil impact or groundwater impact which are commonly used to describe exceedances of regulatory standards at corrective action sites. For this purpose, a vapor intrusion impact is defined as the presence of VOC, or other volatile chemicals, attributable to vapor intrusion in a building at concentrations requiring a response action. The indoor VOC concentration requiring a response action is typically established by the applicable regulatory authority and may be based on considerations of risk, background, and/or analytical detection limits. Although risk-based concentrations are typically based on chronic exposure, many regulatory authorities require a response action to address any measured exceedances of these concentrations including short-term exceedances. Because COC in indoor air may originate from sources other than vapor intrusion, the detection of COC in indoor air at concentrations above a regulatory standard is not sufficient to define a VI impact in all cases. For this report, VI impacts at the demonstration sites have been evaluated in the context of both EPA vapor intrusion guidance (EPA 2002) and the regulatory standards applicable to the individual demonstration sites.

In order to support the primary objective, the following specific data evaluation objectives were established:

1) Characterize the Distribution of VOC Within Environmental Media: Characterize the spatial variability in VOC distribution within specific environmental media. Describe the differences in variability between media. Sample on multiple dates to define both short-term variability (time scale of days) and longer-term variability (time scale of months) in VOC distribution at the demonstration site.

2) Measure VOC Transfer at Saturated/Unsaturated Zone Interface and Throughout Vapor Migration Pathway: Obtain detailed information regarding the mass flux of VOC: i) with depth within the groundwater unit, ii) vertically within the unsaturated soil column, and iii) through the building foundation.

3) Characterize Measurable Site Parameters Related to Vapor Migration Potential: Sample and analyze soils in saturated and unsaturated soil zones and evaluate building characteristics to understand physical parameters that may control potential for and rate of vapor migration including: soil lithology, depth to groundwater, height of capillary fringe, soil hydraulic conductivity and air permeability, soil water retention characteristics, vertical distribution of volumetric moisture content in unsaturated zone, soil organic carbon content, groundwater flow gradient, indoor air exchange rate, building differential pressure, etc.

4) Characterize Vapor Intrusion Mechanisms and Drivers: Conduct detailed analysis of site database to characterize groundwater to vapor transport mechanisms (diffusion in groundwater, groundwater to vapor transfer, vapor diffusion, vapor-structure interaction, VOC mass balance, temporal variation, etc.) and the importance of key site parameters (groundwater concentration, groundwater mass flux, capillary height, soil moisture profile, soil permeability, etc.) to vapor mass flux into the structure.

5) Characterization of Temporal Variability: Collect and analyze multiple samples from fixed sample points to evaluate temporal variability in VOC mass distribution on the time scales of days and months. If possible, correlate changes in mass distribution to seasonal variations in site characteristics such as ambient temperature and seasonal changes in water table elevation.

6) Characterization of Spatial Variability: Collect and analyze samples from closely-spaced sample points to evaluate the significance of spatial variability around individual buildings (i.e., on the scale of 10s of feet). Collect and analyze samples over multiple sample events to evaluate temporal changes in this spatial variability.

Understanding the sources of variability in vapor intrusion data is important for designing VI investigations that maximize the value of information collected with limited resources. For example, if spatial variability is more important than temporal variability then the investigation program would be designed with more sample points but fewer sample events.

Scope of Demonstration: For this demonstration, vapor intrusion site investigations have been completed at a total of three buildings located at two demonstrations sites: two single-family residences near Hill AFB, and a small office building at Altus AFB. At each site, the

investigation program consisted of an initial sample point installation and sampling event and one (Hill AFB) or two (Altus AFB) follow-up sampling events. The sampling program was designed to yield a high density of data around each of the demonstration buildings.

Project Results: The results of this demonstration have been used to generate the following products:

1) Procedural Guidelines for Reliable Evaluation of Vapor Intrusion: A cost-effective and reliable approach for the evaluation of VI. Provided as a White Paper, "Recommendations for the Investigation of Vapor Intrusion".
2) Accessible Site Characterization Database: A web-accessible database presenting the data collected for this project. This database provides VOC concentration results as wells as other site characteristics such as soil parameters and building characteristics. It provides an empirical dataset for evaluation of predictive vapor intrusion models. In addition, the database allows other interested parties to evaluate spatial and temporal variability of VOC in groundwater, soil gas, sub-slab gas, and indoor air.
3) Technology Transfer: A fact sheet and several peer-reviewed publications present key findings that are likely to be useful to state and federal regulators and others responsible for establishing policies related to VI.
4) Permanent and Reusable Monitoring Systems: The monitoring networks installed at the two sites selected for this study have been constructed so as to facilitate future resampling and reuse as desired by DoD. Similar to the Borden Landfill approach, these facilities can be used in future studies to accommodate the continued development and validation of an improved conceptual model and predictive tools for the VI pathway.

1.3 Regulatory Drivers

At a limited number of sites in the U.S., migration of VOC from affected groundwater via vapor phase diffusion has impacted indoor air quality in overlying structures, posing a potentially significant, yet previously unrecognized, human health concern for such properties. The EPA's solid and hazardous waste program established by the Resource Conservation and Recovery Act (RCRA) and the Superfund program established by CERCLA, both utilized risk assessment to determine the need for cleanup of waste sites (EPA 2007). In addition, the Occupation Safety and Health Administration (OSHA) and DoD policy require the maintenance of a safe work environment (US_Air_Force 1993; OSHA 2007). As a result, the potential for vapor intrusion to indoor air must be evaluated at sites with volatile chemicals present in soil or groundwater underlying occupied buildings. To address this concern, the EPA has issued the "Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils," (EPA 2002), providing conservative screening limit concentrations for various VOC in groundwater. The high level of conservatism in the EPA and state guidance reflects the current limitations in our understanding of the physical and chemical processes that contribute to VI. A primary goal of this project has been to support the development of refined vapor intrusion guidance based on an improved understanding of the site-specific factors that influence VI.

As of July 2007, at least 24 states have issued regulatory guidance covering this issue, have guidance under development, or have recommended use of the EPA guidance. Appendix I of this report provides a list of state and federal resources related to VI. The states have adopted a wide range of regulatory approaches that differ in scope and purpose. The results of this investigation are intended to assist the investigator with their understanding of VI processes in order to better apply available technologies to meet the technical requirements of vapor intrusion investigations. The techniques presented in this investigation should be used to support the technical program developed for a specific site and are not intended to address the requirements of all regulatory agencies. A list of web sites providing information on state and federal VI policies is provided in Appendix I of this report.

1.4 Stakeholder/End-User Issues

The EPA Vapor Intrusion Guidance, and many state guidance documents, recommend a step-wise approach for the evaluation of vapor intrusion:

<u>Presence of Volatile Chemicals</u>: VI is a potential concern at sites with soil or groundwater impacted by volatile chemicals. Corrective action sites without volatile chemicals (typically defined by vapor pressure and/or Henry's Law constant) require no further evaluation for vapor intrusion.

<u>Pathway Screening Criteria</u>: At sites with volatile chemicals in soil or groundwater, most regulatory guidance provides conservative screening criteria for preliminary evaluation of the vapor intrusion pathway. Screening criteria are typically provided for groundwater and soil gas and less commonly for soil. These screening criteria are typically used to evaluate whether VOC are migrating away from a source area at concentrations that could cause a VI impact. If the maximum VOC concentration is less than the screening value, then no further evaluation of the vapor intrusion pathway is required. However, for many common COC, the EPA screening criteria for groundwater are equal to drinking water standards. In addition, some soil gas screening criteria are less than, or equal to, analytical detection limits. As a result, many corrective action sites are not screened from further evaluation using these criteria.

<u>Building-Specific Evaluation</u>: For sites with volatile chemicals present at concentrations above the screening criteria, a field investigation is required to determine the presence or absence of VI impacts to near-by buildings (commonly defined as within 100 ft of VOC impacts). When conducting a site-specific field investigation, the EPA guidance recommends collection of below foundation (i.e., sub-slab) gas samples followed by simultaneous below foundation and indoor air samples if needed. The EPA guidance raises a number of data quality issues to be addressed as part of the field investigation including: indoor sources of VOC (background), spatial variability, temporal variability, and duplicate variability. However, the guidance does not provide a clear recommendation on the amount of data needed to account for these sources of variability, and make a definitive

determination about the presence or absence of a VI impact. In the absence of clear guidance on the scope of the field investigation, the investigation approaches adopted by individual investigators has varies widely. As a result, disagreements may arise between parties involved at a site regarding the adequacy of a field investigation.

The results of this demonstration have been used to develop a recommended approach for the cost effective, building-specific, evaluation of VI impacts at corrective action sites (See Section 4.6). Although the understanding of VI processes is still evolving, the investigation approach presented in Section 4.6 has been developed to provide a reliable and cost effective determination of the presence or absence of vapor intrusion impacts at buildings overlying VOC in groundwater or soil. The recommended approach includes a limited-scope initial screening to eliminate buildings with no elevated concentrations of VOC, and a more comprehensive follow-up evaluation program to reliably determine the source of any detected VOC. The stepwise screening and field investigation approach will benefit facility managers by providing investigation results that support a defensible evaluation of VI. In addition, the use of a consistent investigation approach between buildings and sites will provide comparable data sets that support an increased understanding of the factors contributing to VI impacts.

It is important to note that the recommended approach for evaluation of VI impacts may not satisfy all regulatory requirements. The many VI guidance documents currently available provide disparate and sometimes conflicting recommendations. The end user should review the applicable guidance and modify or supplement the recommended approach to ensure that regulatory requirements are satisfied.

2. Technology Description

2.1 Technology Development and Application

Although the scientific and regulatory communities have been aware of the subsurface-to-indoor air VI pathway for over two decades, awareness of this pathway as a potentially significant contributor to human exposure at VOC contaminated sites has increased dramatically in the last seven years. The evaluation of the vapor intrusion pathway has evolved as follows:

- **1980s**: The study of vapor intrusion focuses primarily on radon and landfill gas (Altshuler and Burmaster 1997; Richardson 1997; Folkes and Arell 2003). Due to the uncertainty associated with modeling of radon intrusion into houses, the EPA recommends direct measurement of radon in place of modeling (EPA 2004).
- **1990s**: The potential for vapor intrusion impacts at VOC contaminated sites is primarily evaluated through the use of modeling. The Johnson-Ettinger model (Johnson and Ettinger 1991) extended some of the assumptions originally employed in radon VI models to represent diffusive and pressure-driven (i.e., advective) transport of VOC from a subsurface vapor source to indoor air. In the mid-nineties, several state regulatory agencies and the EPA (EPA 2000) applied the Johnson-Ettinger model, together with conservative

assumptions, to develop risk-based groundwater screening levels that would be protective of human exposure to indoor air impacted by VI.

- **<u>2000s</u>**: The EPA issues draft guidance for the evaluation of VI at VOC contaminated sites (EPA 2001; EPA 2002). EPA guidance limits the use of models for the evaluation of VI and instead recommends the use of conservative screening concentrations and field measurements of VI. Numerous states issue guidance documents, many recommending a screening approach similar to the EPA process.

Although the EPA (2002) has limited the use of predictive modeling for the evaluation of vapor intrusion, the Johnson and Ettinger model still provides the conceptual model most widely used today for the evaluation of vapor intrusion from VOC dissolved in groundwater. This conceptual model is illustrated as Figure 2.1. The key features of this conceptual model include:

- <u>Equilibrium partitioning</u> of VOC between bulk groundwater and the overlying soil gas.
- <u>Diffusion</u> of VOC from deep soil gas to shallow soil gas.
- <u>Advection or diffusion</u> of VOC from shallow soil gas to the base of the building slab then through large cracks or the perimeter seal in the building slab into the building.
- <u>Dilution</u> of VOC in indoor air through exchange with ambient air.

Using this conceptual model, Johnson (2002) identified the critical parameters that are expected to control VI at VOC contaminated sites. Johnson predicted that the critical parameters would vary from site to site depending on the specific mechanism controlling the overall rate of VI as follows:

Vapor Intrusion Limited by Diffusion Through Soil

- Depth to subsurface VOC source
- Soil characteristics including soil permeability, soil saturation, and secondary porosity
- Building air exchange rate

Vapor Intrusion Limited by Diffusion Through Building Foundation

- Foundation characteristics including thickness, area of foundation cracks, and crack permeability

Vapor Intrusion Limited by Advection Through Building Foundation

- Ratio of soil gas intrusion rate to building ventilation rate

Although Johnson (2002) identifies these critical parameters as those site characteristics most likely to determine the magnitude of vapor intrusion impacts at a VOC contaminated site, he does not identify methods to determine which of the three potentially limiting processes is applicable at a specific site.

Although this conceptual model of vapor intrusion has been widely used to develop predictive vapor intrusion models (EPA 2000; Parker 2003) and regulatory guidance, the conceptual model has not been thoroughly validated.

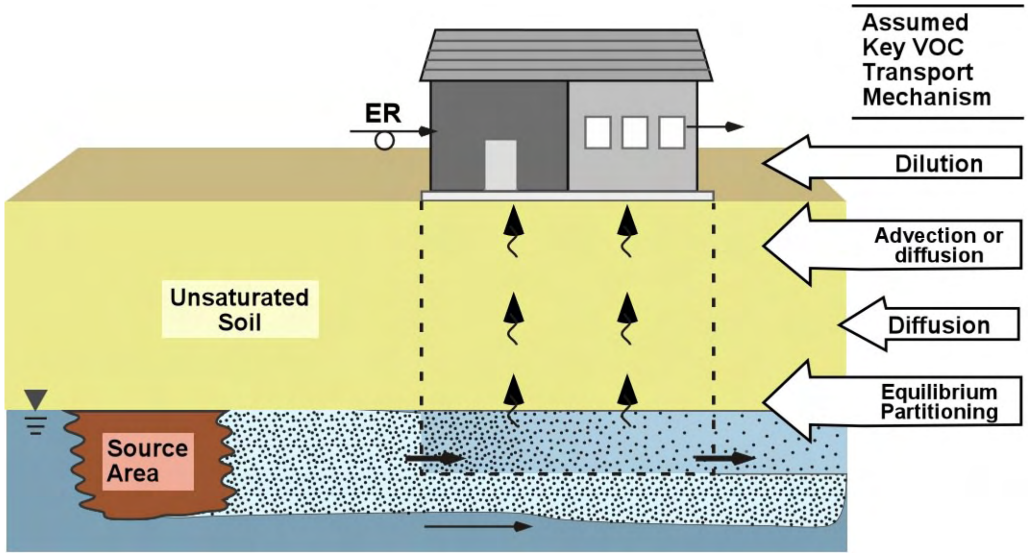


Figure 2.1 Current Conceptual Model for Vapor Intrusion. Limitations of This Conceptual Model are Discussed in Section 2.2.

2.2 Previous Testing of the Technology

The commonly used conceptual model of vapor intrusion described above has been evaluated by a number of researchers resulting in the identification of several areas of uncertainty and the need for further investigation. Key areas of uncertainty in the current groundwater-to-indoor-air vapor intrusion conceptual model are:

- **Johnson-Ettinger Model:** An evaluation of the Johnson-Ettinger Model based on a comparison between predicted and measured VI impacts at ten well characterized sites indicates a typical model error of 100x to 1000x compared to measured indoor air impacts (Hers, Zapf-Gilje et al. 2003; McHugh, Connor et al. 2004b). These results indicate that the Johnson-Ettinger model has limited utility for the evaluation of VI and suggests that the model may not account for key processes that control VI impacts.
- **Consideration of the Water-Soil Gas Interface**: The current conceptual model assumes equilibrium partitioning of VOC between the bulk groundwater plume and the overlying soil gas. In contrast, a number of studies focused on the groundwater-soil gas interface have demonstrated the importance of vertical diffusion in groundwater as the controlling process in the movement of VOC from groundwater to soil gas (Barber, Davis et al. 1990; McCarthy and Johnson 1993; McHugh, Connor et al. 2003). The incorrect and incomplete understanding of the mechanisms of VOC transfer from groundwater to the soil gas phase may contribute to over-estimation of potential vapor intrusion impacts. Detailed

measurements of VOC concentration gradients at the groundwater-soil gas interface are needed to better understand the importance of this transfer to overall vapor intrusion.

- **Vadose Zone Biodegradation**: Although many researchers have identified biodegradation as an important factor in vapor intrusion for many VOC, the current conceptual model does not account for this process. Biodegradation has been identified in a number of studies as the most important factor limiting the vapor intrusion impact of volatile petroleum hydrocarbons (Fischer, Bentley et al. 1996; Lahvis and Baehr 1996; Ririe, Sweney et al. 1998; Roggemans, Bruce et al. 2001). However, for chlorinated VOC, biodegradation appears to be less important at many sites (Hers, Zapf-Gilje et al. 2003). Measurement of the vertical concentration profile of VOC and fixed gasses (i.e., oxygen, nitrogen, carbon dioxide, and methane) in the vadose zone are important for understanding the significance of biodegradation.
- **Site Characteristics**: Roggemans et. al., 2001 looked at 28 sites with VOC contamination and classified them into four groups based on the vertical profile of VOC concentrations in the vadose zone. The researchers, however, were unable to identify the soil or other site characteristics that contributed to the differences in the observed concentration profiles. Measurement of soil characteristics such as grain size, porosity, and saturation, in conjunction with the measurement of VOC distribution, will contribute to a better understanding of the impact of soil characteristics on VOC distribution.
- **Evaluation of Indoor Air Background Conditions**: Background concentrations of VOC in indoor air can vary greatly from building to building, depending on the presence and nature of site-specific indoor sources of these chemicals (paints, adhesives, cosmetics, gasoline, etc.). Consequently, the presence of VOC in indoor air, even at levels in excess of average local or national background concentrations, is not necessarily indicative of actual VI impacts. Conversely, in some cases, vapor intrusion effects may be masked by the magnitude and variability of background VOC concentrations. A thorough characterization of indoor VOC sources is needed to separate indoor VOC sources from actual vapor intrusion impacts (McHugh, Connor et al. 2004a).
- **Reversible Advection Across Building Foundation**: The conceptual model of VI assumes that VOCs move in one direction from the subsurface into the building by advection or diffusion. However, buildings often cycle between positive and negative pressure relative to the subsurface, resulting in reversing advective flow into and out of the building (McHugh, DeBlanc et al. 2006). This advective flow can result in the transport of VOC from the building into the sub-slab, further complicating the evaluation of the vapor intrusion pathway.

In summary, the currently used VI predictive and conceptual models are unable to account for the large variations in VI observed within and between corrective action sites. Intensive characterization of a small number of VOC contaminated sites provides an increased understanding of key VI processes, and serve as the basis to refine the current conceptual model of VI.

2.3 Factors Affecting Cost and Performance

The VI pathway has been subjected to increased regulatory scrutiny in recent years due to the discovery of a limited number of sites with apparent VI impacts. Prior to the discovery of these sites, the vapor intrusion pathway was typically given only cursory consideration during the investigation of corrective action sites and the pathway was rarely a driver in the implementation of response actions. However, recent EPA guidance recommends field investigation of vapor intrusion at many corrective action sites (EPA 2002). This guidance manual contains groundwater screening values for the vapor intrusion pathway that are equal to federal drinking water standards (i.e., MCLs) for many common VOC such as benzene and TCE. Under this guidance, sites with VOC concentrations in groundwater that exceed the screening values will require a field investigation to determine the potential for vapor intrusion. Modeling of the potential for VI is not considered an acceptable alternative to the field investigation.

As a result of the new regulatory guidance, field investigations of vapor intrusion are likely to be required at a large number corrective action sites. Groundwater contamination has occurred at approximately 7,300 DoD corrective action sites located on 1,800 installations (NRC, 1994). Under EPA guidance, a majority of these sites would require field investigations of vapor intrusion due to the presence of either benzene, TCE, or other volatile chemicals at concentrations exceeding federal maximum concentration levels (MCLs).

Although the application of EPA and state VI guidance results in the field investigation of vapor intrusion at many corrective action sites, these documents do not clearly specify the type and amount of field data needed to make a definitive determination concerning the presence or absence of a VI impact. The guidance documents that do address field investigation methods often provide contradictory recommendations. As a result, the type and amount of data required, and the cost of conducting a field investigation, is affected by regulatory project managers and other individuals responsible for site management. Investigation approaches accepted at one site may not be accepted at another site, potentially resulting in wasted effort if site-specific work plans are not pre-approved prior to the investigation.

The performance of a specific VI investigation methods will be influenced by a number of factors including:

- **Spatial Variability**: Variation in VOC concentration between sample points for a single sample event. Spatial variability complicates the VI investigation when the variability cannot easily be attributed, to or associated with, specific site characteristics (e.g., distance from source, sample depth, soil type, surface cover, etc.)
- **Temporal Variability**: Variation in VOC concentration between sample events for a single sample point. Temporal variability complicates the VI investigation when the variability cannot easily be attributed to or associate with measurable changes in site characteristics (e.g., source concentration, depth to groundwater, etc.)

- **Sampling and Analytical Variability**: Variation in VOC concentration results in replicate samples collected from the same sample point. Potential sources of sampling and analytical result variability include true variation in field replicate samples due to small-scale spatial variability (i.e., on the scale of the sample collection volume) or short-term temporal variability (i.e., on the scale of the sample collection time) and low analytical precision for measurements near the analytical detection limit.
- **Confounding Factors**: Contamination and leaks in the sample collection system. Leaks around sample collection points or in sample lines can result in samples that are not representative of actual VOC concentrations at the sample point. Unlike soil or water samples, it is difficult to ensure that a gas sample originated from the location of the sample point. Ambient air may enter the sample container through leaks in the sample lines or around the sample points. Vacuum testing of the sample lines can be used to demonstrate an absence of leaks and leak tracer compounds can be used to evaluate the integrity of both sample points and sample lines.

  Contamination present in re-usable sample containers (i.e., Summa canisters), can result in false positive detections or elevated sample results. For this project, individually certified clean Summa canisters were used to minimize the potential for sample container contamination. Segregation of sample containers between subsurface and above-ground samples can also be used to reduce the potential for carry-over contamination between sampling events.

Investigation approaches that minimize or control these sources of variability will yield more accurate evaluations of vapor intrusion.

2.4 Advantages and Limitations of the Technology

Vapor intrusion into an occupied building will always result in an inhalation exposure to site contaminants, potentially resulting in unacceptable health risks or other conditions that require a response action. Incorrectly concluding that a vapor intrusion impact has not occurred can result in a failure to mitigate the associated health risks and may result in health claims or litigation if the problem is identified in the future. Incorrectly concluding that a VI impact has occurred can result in unnecessary mitigation costs and may also result in litigation or third-party claims. The advantages and disadvantages of vapor intrusion field investigation and presumptive mitigation are discussed below.

<u>Vapor Intrusion Field Investigation</u>: An effective VI field investigation will often yield a definitive determination of the presence or absence of a VI impact. At sites where the investigation demonstrates the absence of a VI impact, no further evaluation of vapor intrusion will be required. At these sites, the available resources can be focused on the evaluation and remediation of other site impacts. At sites where the investigation demonstrates a VI impact, this impact can be mitigated through interim response actions and addressed as part of the comprehensive site remediation.

<u>Presumptive Mitigation</u>: The vapor intrusion pathway is unusual compared to other exposure pathways typically evaluated at corrective action sites because the cost of implementing an exposure prevention remedy is often small compared to the cost of site investigation. The installation of a sub-slab depressurization system is relatively inexpensive ($4,000 to $8,000 per building for a typical single family residence). As a result, the EPA VI guidance recommends installation of sub-slab depressurization systems as a cost-effective alternative to extensive site investigation at sites where VI may be causing indoor air impacts. Based on our current limited understanding of the site-specific factors contributing to vapor intrusion impacts, installation of a sub-slab depressurization system may frequently be more cost effective than conducting a site investigation to determine whether VI is, in fact, a problem. However, this approach has a number of limitations:

- **Perception Problems**: The installation of a depressurization system at a site where a VI problem has not been confirmed may create the perception that an actual VI problem existed prior to the installation of the system. This may create concerns regarding exposure prior to installation of the system, or during periods where the system does not operate, and may increase the risk of litigation and third-party claims.
- **Evaluation of Effectiveness**: Because of indoor air background VOC, it can be difficult to verify that the depressurization system is operating effectively to prevent vapor intrusion. The cost associated with demonstrating system effectiveness, while accounting for indoor air background, may reduce or eliminate the cost savings associated with eliminating the need for the site investigation of vapor intrusion.
- **System-Wide Costs**: Although the cost of a single depressurization system is low, the total cost for multiple buildings over a portfolio of corrective action sites would be quite high. For example, the cost to install depressurization systems at ten buildings at each of 100 sites (1,000 systems total) would be approximately $3,000,000. In addition, significant continuing operation and maintenance (O&M) costs would be incurred.

Due to the high costs associated with i) installing depressurization systems at a large number of corrective action sites or ii) conducting field investigations of vapor intrusion at a large number of corrective action sites, a better understanding of VI processes that supports more effective site investigation procedures have the potential to significantly reduce both site investigation and remediation costs.

3. Demonstration Design

3.1 Performance Objectives

The primary objective of this demonstration study is to identify and validate the limited site investigation scope that provides the most accurate and reliable evaluation of VI at corrective action sites. This objective is met by:

1) Collecting a high density of data related to vapor intrusion at the test sites,
2) Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test sites, and
3) Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

Specific performance objectives cover i) collection of data representative of site conditions and ii) evaluation of the data to identify improved VI investigation methodology. The objectives are summarized in Table 3.1.

Table 3.1: Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	1) Collection of data representative of site conditions.	Precision, Accuracy, Completeness, Representativeness, and Comparability as defined in Table 4.2.1 and Appendix A.	Objective Attained (See Section 4.3)
Quantitative	2) Vapor intrusion impact at Demonstration Site	Indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources	Objective Attained (See Section 4.4.1)
Qualitative	3) Reliable vapor intrusion investigation approach	Accuracy of vapor intrusion determination as characterized by false positive and false negative rates. Identify limited scope investigation approach with higher accuracy than current approaches such as EPA 2002.	Objective Attained (See Section 4.6)

Details concerning the site investigation and data analysis methods used to achieve these performance objectives are provided in Section 4.

3.2 Selecting Test Sites

For this demonstration, sites were selected to maximize the potential to improve our understanding of VOC migration from dissolved groundwater plumes to overlying buildings. The following criteria were used to identify test sites likely to yield interpretable data.

3.2.1 Required Test Site Characteristics

Groundwater Contamination: Test sites were required to have a plume of dissolved volatile chemicals migrating under one or more buildings. The dissolved groundwater plume represented the only likely environmental medium creating a potential for vapor intrusion into the test buildings. In other words, the selected test buildings were located away (i.e., >100ft) from known or likely areas of contaminated soils. Selection of buildings located away from the source area was intended to reduce the potential of vadose zone sources, or lateral migration of vapors, to confound the understanding of vertical VOC migration from groundwater.

Building Access: The sites were required to have one or more buildings overlying the dissolved plume to which access was available for installation of permanent monitoring points through the base of the building and adjacent to the building. Access to the building was required to be available for sample collection over a period of at least one year.

3.2.2 Preferred Test Site Characteristics

Site Characterization: The selected sites were well characterized with regard to site hydrogeology (site stratigraphy, hydraulic conductivity, depth to groundwater, groundwater flow direction, seasonal variability), and the nature and extent of dissolved contaminants.

Depth to Groundwater: Test buildings were selected so that the depth from the base of the building to the top of the groundwater-bearing unit was not less than 3 ft and not more than 25 ft. The minimum depth was specified to ensure the presence of a vadose zone between the buildings and the water table. The maximum depth was specified to provide a reasonable likelihood of detecting a continuous vertical presence of VOC between the groundwater table and the building.

Groundwater Contaminants: Although higher concentrations of dissolved VOC (>0.5 mg/L at depth or >0.1 mg/L at the top of the water table), were identified as a desired characteristic, the selected demonstration sites had VOC concentrations at the top of the water table typically ranging from 0.002 to 0.004 mg/L. Despite the relatively low dissolved VOC concentrations, these sites were determined to have the best overall site characteristics for the demonstration.

3.3 Test Site Description

3.3.1 Altus Air Force Base, Altus, Oklahoma

The first location selected for the field vapor intrusion investigation was in and around Building 418 on Altus AFB, located near the southern boundary of the facility. A map of the facility, including the location of Building 418, is presented in Appendix C, Figure 4.5.1-2. The groundwater plume underlying the test building has been extensively characterized as part of the RFI process underway at Altus.

The test building is a single-story slab-on-grade office building approximately 150 ft long by 50 ft wide. The building is used primarily for classroom instruction. Based on the small size and non-industrial use, the building is representative of large houses, small apartment buildings, and small office buildings. The test building is underlain by a shallow dissolved chlorinated solvent groundwater plume containing elevated concentrations of PCE, TCE, and 1,2-DCE. This plume has been designated the SS-17 plume.

The local subsurface geology consists of clay, sandy clay, residual soils resulting from the weathering of shale, and alluvium resulting from the erosion and deposition of surface materials (which includes fill associated with construction activities). The fill, clay, disturbed residual soils, and alluvium are difficult to separate and are collectively referred to as the sediment/overburden. This sediment/overburden appears to cover the entire site.

The transition from sediment/overburden to the more competent shale is not a readily defined horizon, however, the sediment/overburden is generally considered to extend 12 to 20 ft below ground surface in the vicinity of building 418. In general, the extent of weathering within the shale becomes less with depth. Both the vertical and horizontal migration of chlorinated VOC at SS-17 have been influenced by the permeability of the subsurface materials that can be enhanced by the weathering process. Geologic cross-sections extending from the north-west to the south-east and from the west to the east are presented in Appendix C, Figures 4.5.1-2, 4.5.1-3, and 4.5.1-5.

The potentiometric surface within the sediment/overburden is located 3 to 10 ft bgs and varies seasonally by up to 4 ft. An evaluation of the potentiometric surface reveals a range of hydraulic gradients from 0.0006 ft/ft to 0.0048 ft/ft, with groundwater flow to the southeast. The overall hydraulic gradient from the northern portion of SS-17 to the southeast portion of SS-17 is 0.004 ft/ft. Within the area of the SS-17 groundwater plume, the hydraulic conductivity values range from 7×10^{-4} cm/sec to 9×10^{-3} cm/sec. Based on calculations using the range of observed gradients, conductivities and porosities, groundwater seepage velocities across the area impacted by the SS-17 plume range from 6.5×10^{-3} ft/day to 5.6×10^{-1} ft/day. A potentiometric surface map of the shallow water-bearing-unit underlying the test area is provided as Figure 4.5-2 in Appendix C.

The SS-17 plume has been characterized through the installation and sampling of over 225 monitoring wells including 135 shallow wells, 81 medium depth wells, and 14 deep wells. The shallow wells generally have 10 ft screens with top-of-screen depths ranging from 3 to 7 ft bgs. The medium depth wells typically have 10 ft screens with top-of-screen depths of 28 to 32 ft bgs.

This network of wells has served to delineate a TCE plume approximately 4000 ft long and 1200 ft wide, originating from two buildings located 500 and 800 ft north of the test building, resulting in TCE concentrations of approximately 200 ug/L in groundwater below the test building. Smaller plumes of PCE and 1,2-DCE appear to originate in the same areas and also extend under the test building. Isoconcentration maps of TCE, PCE and DCE plumes are provided in Appendix C as Figures 4.5.1-17, 4.5.1-22, and 4.5.1-20, respectively.

In order to provide an overview of key site information, the following figures have been included as Appendix C.

- Figure 4.5.1-2 SS-17 Cross-Section Location Map
- Figure 4.5.1-3 SS-17 Geologic Cross-Section 5A-5A'
- Figure 4.5.1-5 SS-17 Geologic Cross-Section 5C-5C'
- Figure 4.5.1-17 SS-17 Groundwater TCE Isoconcentration Map Upper Wells, 2001
- Figure 4.5.1-22 SS-17 Groundwater PCE Isoconcentration Map Upper Wells

- Figure 4.5.1-20 SS-17 Groundwater DCE Isoconcentration Map Upper Wells
- Figure 4.5-2 Group 5 Potentiometric Surface Map, Upper Wells, May 2001

3.3.2 Hill Air Force Base, Ogden, Utah

The second vapor intrusion field investigation was conducted at Operable Unit 5 (OU-5), a dissolved TCE plume originating on Hill AFB near Ogden, Utah, and extending off-base to the west. The investigation focused on two residential houses overlying this TCE plume. A map of the area showing the location of the 2 buildings is presented in Appendix C, Figure 2-3. The first residence (Residence 1) is located near the corner of 690 West and 2550 North in the community of Clinton. TCE concentrations in shallow groundwater in the vicinity of this residence are between 10 and 100 ug/L. The second residence (Residence 2) is located near the corner of 175 West and 2125 North in the community of Sunset. TCE concentrations in shallow groundwater in the vicinity of the test building are around 100 ug/L.

The shallow groundwater-bearing unit underlying OU-5 is characterized by fine grain sand and silt, with the silt content increasing with depth. The upper portion of the unit is characterized by fine to very-fine grained yellowish-brown sand. The silt content generally increases with depth, grading into a clay at 20 to 30 ft below ground that serves as a confining layer isolating shallow groundwater from deeper water-bearing units. This clay unit is made up of 85 to 95 percent silt and clay particles and is a dark grayish-brown clayey silt of low permeability. COC impacts have been observed in the shallow groundwater-bearing unit but not in the underlying confining layer or deeper water-bearing units. Geologic cross-sections extending from west to east (each plume) and north to south, depicting the groundwater-bearing unit and low permeability unit, are presented in Appendix C as Figure 3-9, 3-10, 3-11, and 3-12 from the 2002 Remedial Investigation report.

The shallow groundwater found at OU-5 is unconfined and the depth to groundwater is generally 4 to 10 ft bgs. The water table is seasonally variable with the average difference in groundwater elevation between spring and fall being 1.7 ft. In the vicinity of the first residence, the water table is 6 to 8 ft bgs. In the vicinity of the second residence, the water table is 4 to 6 ft bgs.

An evaluation of the potentiometric surface reveals horizontal hydraulic gradients ranging from 0.01 to 0.05 feet per foot (ft/ft) with a mean of about 0.03 ft/ft. The overall gradient at OU-5 is to the northwest in the source areas and then to the west as the plume moves off of the AFB. Horizontal hydraulic conductivity at OU-5 ranges from 0.006 to 225 ft/day with a geometric mean of 2.8 ft/day. A potentiometric surface map of the shallow water-bearing unit underlying OU-5 is presented in Appendix C as Figure 3-14.

Average groundwater seepage velocities in the region have been determined using estimated horizontal hydraulic conductivity and horizontal gradient data from each well

location. An effective porosity of 30 percent was used in calculating the groundwater velocity based on an average total porosity for the area of 37 percent. The calculated groundwater velocity ranges from 0.01 to 12.4 ft/day with a geometric mean of 0.3 ft/day (100 ft/year).

There are a number of contaminants present in the shallow groundwater underlying OU-5 with TCE being predominant. The affected groundwater moves west from Hill AFB as two distinct TCE plumes: a north plume (identified as the Zone 16 plume in the RI) and a south plume (identified as the TARS plume). Residence 1 is located above the Zone 16 plume while Residence 2 is located above the TARS plume (see Appendix C, Figure 2-3). In the Zone 16 plume, maximum off-site concentrations of TCE are generally less than 100 ug/L. TCE concentrations decrease gradually from west to east with elevated TCE concentrations extending approximately 7000 ft off the base. In the TARS plume, the maximum off-site concentrations of TCE are generally less than 1,000 ug/L. TCE concentrations decrease gradually from west to east with elevated TCE concentrations extending approximately 6000 ft off the base. An isoconcentration map showing the extent of the TCE plumes is provided in Appendix C as figure 3-14. Concentrations of VOCs other than TCE are generally less than 10 ug/L in areas off-base, and the pattern of detections does not indicate continuous areas of elevated concentrations.

In order to provide an overview of key site information, the following figures have been included as Appendix C.

- Figure 2-3 Extent of TCE in Groundwater and Monitoring Well Location Map
- (December 2002)
- Figure 2-7 Residential Air, Water, and Surface Soil Location Map
- Figure 3-9 OU-5 Cross Section Location Map
- Figure 3-10 OU-5 Cross Section A-A'
- Figure 3-11 OU-5 Cross Section B-B'
- Figure 3-12 OU-5 Cross Sections C-C', D-D', and E-E'
- Figure 3-14 OU-5 Potentiometric Surface and TCE Isoconcentration Map
- Figure 4-5 OU-5 Extent of TCE Contamination with Concentration vs Time Graphs for TARS Plume.

In order to reduce TCE concentrations, two remediation systems were installed in 1997 within the TARS plume upgradient of Residence 2. The first system (Phase I Aeration Curtain) consists of an air sparge system and a soil vapor extraction (SVE) system located on Main Street in Sunset (see Figure 2-3 in Appendix C). This system is located approximately 1000 ft upgradient of Residence 2. The second system (Phase II Groundwater Extraction System) consists of 5 groundwater extraction wells spaced 25 feet apart and is located at 2125 North and 55 West in the City of Sunset. The flow of groundwater through this area is 3 times greater than the groundwater recovery rate of the systems, and is therefore insufficient to contain TCE plume. Since activation of these

two systems, TCE concentrations in the upgradent portion of the plume have decreased, however, little change in TCE concentration has been observed in the vicinity of Residence 2 (i.e., see monitoring well U5-1072 on Figure 4-5). As a result, the operation of these groundwater treatment systems is not expected to impact the VI demonstration study.

3.4 Pre-Demonstration Testing and Analysis

3.4.1 Altus Air Force Base, Altus, Oklahoma

The groundwater plume underlying the test building at this site was extensively characterized as part of the RFI process underway at Altus. Documentation of the RFI investigation is provided in the draft RFI/IA/CMS Report issued November 4, 2002. This report provided sufficient site characterization information to support the location and design of the field equipment for investigation of vapor intrusion processes. As a result, no additional pre-demonstration testing was required for this test site.

3.4.2 Hill Air Force Base, Ogden, Utah

The two TCE plumes underlying the test site were thoroughly characterized by a series of investigations beginning in 1987 and resulted in the installation of approximately 300 temporary or permanent groundwater sampling locations.

In addition, indoor air quality has been tested in over 160 homes over or adjacent to the OU-5 TCE plumes. Chlorinated VOC have been detected at concentrations above action levels in approximately 2% of homes tested and detected at concentrations below action levels in approximately 3.5% of homes tested. When requested by the residents, mitigation systems have been installed in any home where VOC have been detected. VOC have not been detected in Residence 1 and have been detected below action levels in Residence 2. Mitigation systems have not been installed in either home.

3.5 Testing and Evaluation Plan

3.5.1 Demonstration Installation and Start-up

For this site investigation demonstration, the installation program consisted of the installation of subsurface sample points. Sample points were installed at Altus AFB in March 2005 and at Hill AFB in August 2005. A total of 27 subsurface sampling points were installed around and under each of the three demonstration buildings (See Figures G.3, G.4, G.5, Appendix G).

Groundwater Monitoring Well Points: Monitoring wells for groundwater and well headspace sampling were installed using traditional direct push techniques. Three monitoring well clusters were installed around each building with each cluster consisting of four wells with vertically spaced screens. Borings were advanced with a track-mounted Geoprobe unit to depths specified by the demonstration plan. Based on the

expected static water level, the four monitoring wells in each cluster were installed so that the shallowest well would be at the top of the water table during periods of the highest expected water table elevation. The remaining three wells were set with each screen at a depth 2 ft below the previous well. The deepest boring was advanced first and was used to log the shallow geology. The next deepest boring was used to collect 3 representative samples for geotechnical analysis. The remaining two borings were advanced with no sample collection or logging.

Monitoring wells were constructed of one inch schedule 40 polyvinylchloride (PVC) pipe with flush threaded joints. The well screen consists of one ft of number ten slotted PVC with a threaded cap on the bottom with no sump. The screened interval of the well was packed with U.S. mesh interval 20/40 sand. The remainder of the borehole was filled with bentonite chips and hydrated to create an annular seal. Monitoring wells were capped with a tight fitting PVC slip cap. Monitoring wells were completed at the surface using an aluminum flush mount man-way installed in a concrete pad or existing surface asphalt or concrete cover. Photo 3.5.1.1 shows monitoring well and soil gas points at Altus AFB prior to completion of the surface pad. Example construction specifications are shown on Figure A.1, Appendix A.

Figure 3.5.1.1: Soil Gas and Monitoring Well Cluster Prior to Pad Completion (Altus AFB).
Note: Larger 1” diameter casings are the monitoring wells, smaller 1/2” casings are the soil gas points.

Soil Gas Points: Two vertical clusters of soil gas points were installed outside, adjacent to each demonstration building and one vertical cluster was installed through the building foundation. The soil gas points installed outside were installed in the same manner as the monitoring wells using direct push techniques to depths of 1, 2, 3, and 4 ft bgs. Soil gas points were installed outdoors at the upgradient and downgradient cluster locations. The

outdoor soil gas points were constructed of ½ inch diameter schedule 40 PVC pipe with flush threaded joints. The sample screen consisted of two inches of number ten slotted PVC with a threaded cap on the bottom. A sand pack using U.S. mesh interval 20/40 sand was installed around the screen and extended several inches above the screened interval. The remainder of the borehole was filled with bentonite chips and hydrated to create an annular seal. Soil gas sampling points were capped with a tight fitting PVC slip cap. Outdoor soil gas points were completed using an aluminum flush mount man-way installed in the existing surface cover or in a 4 ft x 4 ft concrete pad, as described for the monitoring wells. Example construction specifications are shown on Figure A.1, Appendix A.

Indoor soil gas points were installed at the midgradient cluster to depths of 1, 2, 3, and 4 ft bgs. At Altus AFB, an additional sample point was installed at a depth of 5.5 ft bgs. However, this point was not specified in the original demonstration plan, but was added as a supplemental point during implementation of the field program. No samples could be obtained from this point due to a lack of air flow through the point. As a result, this point is not discussed further. Boreholes for the indoor soil gas points were advanced using a ¾ inch steel rod driven to the correct depth through a one inch hole bored in the building's concrete slab. The sample points consisted of an aluminum point with a hollow screened area with a port for attachment of sampling tubing. This sample point was attached securely to 1/8th inch Nylaflow tubing and lowered to the bottom of the boring. Coarse sand was installed around the point and up to several inches above the point. The borehole was sealed from atmospheric air by one to two feet of cement pumped into the borehole immediately above the sand pack. Example construction specifications are shown on Figure A.1, Appendix A and completed points are shown in Photo 3.5.1.2.

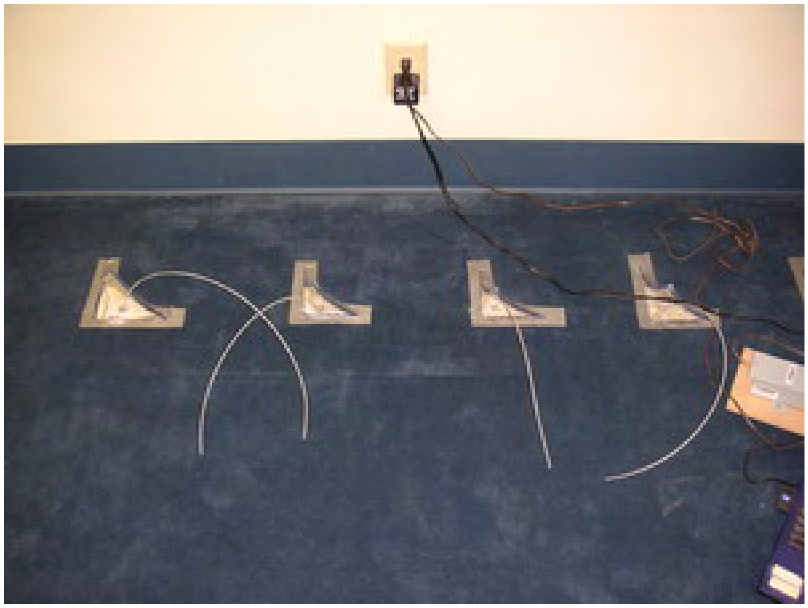


Figure 3.5.1.2 Indoor Soil Gas Points.

Sub-Slab Sample Points: Sample points for the collection of sub-slab gasses were installed by drilling a ½ inch hole through the building slab and into the underlying soil or fill material to a depth of 3 to 4 inches below the base of the foundation. A 3/16th inch stainless steel tube attached to a female ¼ inch compression fitting was installed in the hole to a depth roughly equivalent with the bottom of the slab. An annular seal was created by placing cement around the stainless steel tube and the compression fitting. The sample point was completed by the installation of a threaded plug that was flush with the foundation after installation. The ¼ inch threaded compression fitting allowed for the attachment of a sample train for sample collection. Example construction specifications are shown on Figure A.1, Appendix A and a completed point is shown in Photo 3.5.1.3.

Figure 3.5.1.3 Sub-Slab Sample Port.
Note: Picture shows capped sample port installed in foundation slab with flush threaded plug. Masking tape was applied carpet before cutting to maintain the integrity of the carpet and hold the carpet out of the way while sampling. Cut in carpet was sealed with commercial carpet glue between sample events.

3.5.2 Period of Operation

Initial sampling events were conducted the week after installation of the sampling points at each demonstration site (Altus AFB in March 2005 and Hill AFB in September 2005). In order to characterize temporal variability, three follow-up sampling events were conducted at Altus AFB (March 2005, July 2006, and December 2006) and one follow-up sampling event was conducted at Hill AFB (March 2006).

3.5.3 Amount /Treatment Rate of Material to be Treated

Because this was a site characterization demonstration, no treatment was conducted.

3.5.4 Residuals Handling

Because this was a site characterization demonstration, minimal volumes of residuals were generated. All monitoring points were installed using direct push technology, minimizing the volume of residual soils produced. Groundwater samples were collected using low flow, low purge techniques, minimizing the volume of purge water generated. Potentially affected soil cores and purge water was collected in 5-gallon buckets and left with on-site environmental personnel for proper disposal.

3.5.5 Operating Parameters for the Technology

Because this was a site characterization demonstration, operating parameters are not applicable. Sample collection procedures are described in Section 3.5.7.

3.5.6 Experimental Design

This demonstration was designed to collect a high density of data focused around individual test buildings in order to obtain a thorough understanding of VI processes at the location. This high density data set was used to:

- Evaluate sample collection and analysis methods.
- Evaluate and refine the current conceptual model of vapor intrusion, as described in Section 2 of this report.
- Identify key environmental interfaces and site physical characteristics that impact the movement of VOC along the vapor intrusion pathway.
- Identify and validate a limited-scope site investigation to accurately evaluate vapor intrusion at corrective action sites.

In order to support these objectives, a sample collection program was designed as described below. Data analysis and interpretation are described in Section 4.4.

Sample Network: In order to provide a high density of data around individual buildings, a network of sample points was installed at each demonstration building consisting of: three clusters of four vertically-spaced groundwater wells, three clusters of four vertically-spaced soil gas points, three sub-slab sample points, three indoor air sample points (with additional indoor air points for indoor tracer gas analyses), and three ambient air sample points. A conceptual illustration of the sample point network is provided as Figure E.1. The sample point locations around the three demonstration buildings are provided in Appendix G, Figures G.3, G.4, and G.5.

Types of Samples Collected: For each sampling event, samples were collected from each sample point and analyzed for VOC concentration. Additional analyses were conducted to understand the impact of site conditions on the distribution of VOC around the demonstrations buildings:

- *Geotechnical Data*: Soil samples collected during installation of the monitoring wells and soil gas points were analyzed for bulk density, fraction organic carbon, total porosity, water saturation, intrinsic permeability, and native hydraulic conductivity.
- *Oxygen and Carbon Dioxide*: During the initial sampling event at each site, subsurface samples were analyzed for oxygen and carbon dioxide. These analyses were not included in the subsequent sampling events based on the low variation in concentration observed between samples for these analytes.
- *Radon Analyses*: Sub-slab, indoor, and ambient air samples were analyzed for radon in order to evaluate the movement of soil gas through the building foundation.
- *Indoor Tracer*: Sulfur Hexafluoride (SF_6) was released inside each demonstration building during each sample event and measured indoor SF_6 concentrations were used to evaluate building air exchange rates. For some follow-up sampling events, SF_6

concentrations were measured in sub-slab samples to evaluate air flow from the building through the foundation.

- *Leak Tracer*: For soil gas samples collected adjacent to the demonstration buildings, a leak tracer (pentane, 1,1-difluoroethane, or SF_6) was used to evaluate the integrity of the sample points and sample collection lines.
- *Cross-Foundation Pressure Gradient*: During each sampling event, the cross-foundation pressure gradient was measured over a period of at least 24 hours.
- *Soil Permeability*: During the follow-up sample events, soil permeability was measured at selected soil gas points and unsaturated monitoring well locations by measuring the vacuum induced at various air flow rates.
- *Building Depressurization*: During the follow-up sampling at Hill AFB Residence #1, the impact of induced negative building pressure on indoor air quality was evaluated. For this evaluation, additional indoor and sub-slab samples were collected for VOC, radon, and SF_6 analyses.

In order to ensure that data were comparable between buildings and between sample events, the sample point design was not varied between buildings. Sample collection and analysis methods were also consistent from event to event, however, minor changes to the sampling program were implemented based on lessons learned during the early sampling events.

Sample Events: At least two sampling events were conducted at each demonstration building. The sample events are described below and summarized in Table 3.5.6.1.

- *Sample Point Purge Study*: Prior to the first full sample event at each location, a purge study was conducted on the soil gas sample points to evaluate the impact of sample point purge volume on measured VOC concentration. Based on the results of these studies (see Section 3.5.7), a purge volume of 3 sample line volumes was used for collection of subsequent samples.
- *Initial Sampling Event*: At each location, an initial sampling event was conducted approximately one week after installation of the subsurface sampling points. For the initial sampling event, samples were collected and analyzed for VOC, oxygen and carbon dioxide, geotechnical analyses, radon, indoor tracer, and leak tracer.
- *Evaluation of Short-Term Variability (Days)*: At the Altus AFB demonstration building, samples were collected two days after the initial sampling event. The results of these analyses were used to evaluate temporal variability on the time scale of days. For this sampling event, samples were collected and analyzed for VOCs and radon.
- *Evaluation of Longer-Term Variability (Months)*: At the Altus AFB demonstration building, follow-up sampling events were conducted 16 months and 22 months after the initial sampling event. At the two Hill AFB demonstration buildings, follow-up sampling was conducted six months after the initial sampling event. For these sampling events, samples were collected and analyzed for VOC, radon, indoor tracer, and leak tracer. In addition, soil permeability was measured at selected points.

- *Building Depressurization*: The building depressurization study was conducted at Hill AFB Residence #1 immediately after the follow-up sampling event.

Table 3.5.6.1: Summary of Sample Collection by Sampling Event.

Sample Event	Sample Type							
	VOC	Soil Geotech.	O_2 / CO_2	Radon	Indoor Tracer	Leak Tracer	Soil Perm.	Building Depress.
Altus AFB Building #418								
Soil Gas Point Purge Study	X					X		
Initial Sampling Event	X	X	X	X	X			
Short-Term Follow-up	X		X	X				
Longer-Term Follow-up #1	X			X	X	X	X	
Longer-Term Follow-up #2	X			X	X	X	X	
Hill AFB Residence #1								
Soil Gas Point Purge Study	X					X		
Initial Sampling Event	X	X	X	X	X			
Longer-Term Follow-up	X			X	X	X	X	
Building Depressurization	X			X	X			X
Hill AFB Residence #2								
Soil Gas Point Purge Study	X					X		
Initial Sampling Event	X	X	X	X	X			
Longer-Term Follow-up	X			X	X	X	X	

Data Quality Objectives: To ensure that data from this project conformed to known and acceptable levels of quality, quantifiable data quality objectives (DQO) were developed for accuracy, precision, and completeness. Quality assurance requirements for field samples included field duplicates, matrix spike/matrix spike duplicate (MS/MSD) pairs, trip blanks, and equipment rinsate blanks. Accuracy and precision objectives for laboratory analyses were based upon historic recovery and relative percent difference data obtained from EPA SW-846 and other appropriate guidance. Method quantitation limits (MQL) were provided for constituents analyzed during the work program. Acceptable levels of comparability were assured through the implementation of standard field and laboratory protocols.

Detailed data quality objectives are specified in the QAPP included as Appendix B.

3.5.7 Sampling Plan

Sample Collection: The typical sample collection and analysis program is summarized in Table 3.5.7.1.

Site Physical Characteristics: During installation of groundwater monitoring wells, soil cores were collected and analyzed for key soil parameters that influence the vertical migration of vapors: air permeability, air-filled porosity, grain density, dry bulk density, moisture content, and fraction organic carbon. Three soil cores were collected from each of the three multi-level monitoring well cluster locations for a total of nine samples from each site. At each location, three depths within the unsaturated soils were selected for analysis based on the observed lithology. The three soil cores submitted for analysis were selected so as to be vertically distributed and to be representative of any observed variability (i.e., more and less permeable soils).

As part of the installation of the multi-level monitoring wells, four soil cores were generated at each location, one for each monitoring well. Lithology was characterized using one core, while a second core was retained intact for collection of the geotechnical samples. Soil core intervals selected for analysis were cut from the intact core, retained within the coring sleeve, capped, and packed on ice for shipment to PTS Laboratories in Houston, Texas. The two remaining cores were discarded if they were not needed for characterization of lithology or collection of geotechnical samples.

As described in Section 3.3, previous site investigations had determined key hydrogeologic parameters for the saturated units such as aquifer hydraulic conductivity, flow gradient, soil lithology, and depth to groundwater.

Sample Point Purge Volumes: For sub-slab and soil gas sample collection points, a purge study was conducted prior to the first site characterization sampling event in order to determine the appropriate volume of soil gas to purge in order to obtain a sample representative of actual subsurface conditions. One of each type of subsurface sampling point was included in the purge volume study (i.e., sub-slab, shallow soil gas, medium soil gas, deep soil gas, and well headspace). The purge volume study was conducted as follows:

- The volume of the sampling point and all sampling lines downstream of the sample collection vessel (i.e., sample line volume) were determined.
- One sample line volume was purged from the sample point followed by collection of a grab sample.
- An additional volume was purged so that the total purge volume, including the volume collected for the first sample, was equal to two sample line volumes.
- This process was repeated such that samples were collected following purging of one, two, four, and eight sample line volumes.

- During the purging and sample collection, a tracer gas was released at the ground surface in order to evaluate the seal between ground surface and the sample point.
- The four samples were analyzed for VOC and tracer gas in order to determine the range of acceptable purge volumes yielding samples representative of sample point conditions.

Changes in target COC concentration were used for evaluation of the purge study results. The COC concentrations measured in the samples typically increased between 1 and 2 purge volumes and were stable or slightly increasing from 2 to 8 purge volumes (see Appendix G of this report for the full data set). COC concentrations were most stable in the sample points with the lowest total line volumes. Based on these results, a purge volume equal to 3 line volumes was selected as a volume sufficient to ensure thorough flushing of the sample collection lines but low enough to minimize the flow of gas in the subsurface around the sample collection point induced by the sample collection process. In addition, 1/8th inch nylaflow tubing was used for sample collection to minimize required purge volumes.

Groundwater Samples: Prior to sampling, all groundwater sampling points were gauged to determine whether groundwater had infiltrated the well and to measure the static water level. Monitoring wells installed for the demonstration project were pumped dry using a peristaltic pump with dedicated tubing and allowed to recharge prior to the sampling event. Following recharge, groundwater was collected using the peristaltic pump and placed in method-specific containers, 40 mL VOA vials. During the sampling event, physical properties such as temperature, specific conductance, and pH were measured if there was a sufficient sample volume.

Gas Samples: Gas samples were collected using a variety of methods depending on the planned sample analyses. For subsurface gas samples, three line volumes of gas were purged from the sample train prior to sample collection. For samples analyzed in the on-site mobile laboratory, samples were collected using a 60 mL gas tight syringe. The syringes were equipped with a 3-way valve that allowed for sealing the syringe following sample collection. Filled syringes were immediately delivered to the on-site mobile lab for analysis within one hour of sample collection. The syringe and 3-way valve sampling system used for sample collection is shown on Appendix A, Figure A.1. Subsurface gas samples analyzed off site for VOC and fixed gases were collected in 400 mL Summa canisters or 1 L Summa canisters back-filled with 600 mL of inert gas. A vacuum gauge incorporated in the summa canister sample train was used to monitor the vacuum and ensure sample collection. The summa canister sampling system is shown in Appendix A, Figure A.1. Indoor and ambient air samples analyzed off site for VOC were collected in 400 mL Summa canisters (Altus AFB initial sample event) or 6 L Summa canisters (all other sample events). Samples collected for radon analysis or off site SF_6 analysis were collected using a 60 mL gas tight syringe and transferred to a 500 mL Tedlar bag or other

gas tight container for shipment. Additional indoor radon samples were collected using a commercially available passive system of activated carbon exposed to the indoor air for 48 to 72 hours. Per the manufacturer's instructions, the canisters were left open for a minimum of 48 hours then resealed and shipped to the laboratory for analysis. All gas samples were collected as grab samples except for samples collected in 6 L Summas. 6 L Summa samples were collected as 24-hour composites.

Well headspace and outdoor soil gas samples were collected by attaching a modified sample point cap to the top of the well casing. This cap contains a stainless steel bulkhead fitting that allows the 1/8 inch Nylaflow tubing to pass through the PVC cap and retain a seal. The Nylaflow tubing was extended down to just above the static water level in the monitoring well. The very small diameter of the sample line resulted in very low purge volumes and minimal disturbance of the subsurface gases being collected. This system allowed the monitoring well or soil gas point to be sealed from the atmosphere during sample collection. The sample train was flushed with ambient air between sampling points. This sample collection method is depicted on Appendix A, Figure A.2 and is shown in Photos 3.5.7.1 and 3.5.7.2.

Figure 3.5.7.1 Soil Gas Sample Point with Sampling Apparatus Attached.

Soil gas samples were collected from the indoor soil gas sample points by attaching the sampling train to the 1/8th inch Nylaflow tubing extending up through the slab from the subsurface sample point (Appendix A, Figure A.1). Sub-slab gas samples were collected by attaching the sample train to the top of the threaded sample port (Appendix A, Figure A.2). The sample line volume of the sub-slab sample point was estimated to be 10 mL total.

Figure 3.5.7.2 Cap Used for Soil Gas and Well Headspace Sampling.

Indoor Air Quality Survey: During each initial sampling event, a survey of indoor air quality was conducted to identify any potential sources of VOC in the building. A ppbRAE photoionization detector (PID) meter that allows for detection of total VOC at ppb levels was used for the survey. The meter was placed into survey mode and carried throughout all of the accessible rooms in the demonstration buildings. No indoor VOC sources were detected through these surveys.

Building Air Exchange: A tracer gas, SF_6, was used to evaluate the indoor air exchange rate, the rate of air exchange between the building and ambient air. The indoor air exchange rate was measured by releasing SF_6 within the building and then measuring the steady state concentration at various locations in the test buildings. SF_6 was released in central areas of the buildings and the concentration measured by the collection of samples after steady state conditions were achieved (~18 hours). By using a tracer gas, the building air exchange rate can be accurately measured without the problem of background interference posed by the common VOC found at corrective action sites. During the follow-up sample events, samples collected from below the building foundation (sub-slab and below foundation soil gas) were also analyzed for SF_6 to evaluate the movement of the tracer gas into the subsurface.

Pressure Gradient Across Building Foundation: In order to understand the potential for advective flow across the building foundation, the pressure gradient across the building foundation was measured using an Omega PX-10DI or Omniguard four differential pressure transducer with data logger. These pressure transducers can measure positive and negative pressures gradients, providing an indication of advective forces into and out of the building. The cross-foundation pressure gradient was measured during all sub-slab and indoor air sample collection events and over a minimum 24-hour period reflecting typical building operating conditions. The pressure transducer contains two pressure ports, a reference port open to the indoor atmosphere, and a second port isolated in the sub-slab atmosphere by tubing extending through the building slab and sealing it from the

indoor atmosphere. This apparatus, shown in Photo 3.5.7.3, allows for the direct measurement of the differential pressure between these two areas.

Figure 3.5.7.3 Pressure Transducer Installed to Measure Cross-Foundation Pressure Gradient.

Vadose Zone Permeability Testing Procedure: Vadose zone permeability was evaluated at the demonstration buildings during the follow-up sampling events after all sample collection was completed. For each sample point tested, soil gas was extracted by applying a vacuum to the soil gas monitoring point. The flow rate was controlled by adjusting valves on a laboratory-grade flow meter and steady-state vacuum was recorded for at least three flow rates. The soil permeability at each sample point was calculated based on flow rate and vacuum as described in Appendix E.

Sample Analysis

Geotechnical Samples: Geotechnical soil samples were analyzed for bulk density, fraction organic carbon, moisture content/saturation, porosity, permeability, and hydraulic conductivity. Geotechnical analyses were performed by PTS Laboratories in Houston, Texas, according to applicable ASTM, EPA, and API methods as outlined in the QAPP, included as Appendix B.

Groundwater Analysis: Groundwater samples were submitted to Severn Trent Laboratories in Houston, Texas, and analyzed for VOC by EPA Method SW846 8260B (8260B).

<u>*Gas Sample Analysis*</u>: Gas samples collected in 60 mL syringes (initial sample events) were analyzed using an on-site mobile laboratory operated by H&P Mobile Geochemistry of Solana Beach, California. Samples were analyzed for VOC by 8260B using purge and trap sample delivery and a mass spectrometer (MS) detector. The majority of these samples were analyzed with the MS detector in Selective Ion Monitoring (SIM) mode, allowing for detection limits comparable to those specified in the QAPP for EPA Method TO-15. Samples for off-site analysis were collected in 400 mL, 1 L, or 6 L summa canisters for analysis of VOC by EPA Method TO-15 (all sample events) and O_2 and CO_2 by ASTM Method 1945-96 (initial sample events). Samples collected using 6 L Summa canisters (i.e., ambient and indoor samples) were analyzed by EPA Method TO-15 SIM to achieve lower detection limits.

Gas samples for radon analysis were analyzed by Dr. Doug Hammond at the University of Southern California Department of Earth Sciences using the extraction method of Berelson, 1987 and the analysis method of Mathieu, 1998. This analysis does not have a defined detection limit, however, measurement accuracy decreases with decreasing radon concentration. The measurement accuracy for a sample containing 0.2 pCi/L radon is estimated to be +/-30% (McHugh et al., 2006b). Ambient radon concentrations range from 0.2 to 0.7 pCi/L (EPA, 1993), indicating that ambient radon concentrations can be measured with an accuracy of +/-30% or better. Additional radon samples collected by means of pre-weighed activated carbon canisters were analyzed using EPA Method #402-R-93-004 079 and had a method detection limit of 0.4 pCi/L.

Gas samples requiring SF_6 analysis were analyzed using a modified NIOSH 6602 method which utilizes a gas chromatograph with electron capture detector (ECD).

Table 3.5.7.1: Summary of Sample Collection and Analysis Program for a Typical Sampling Event.

Matrix	Number of Samples	Sample Volume	Container	Analytical Method	Holding Time	Lab	Sample Collection Timing
GW	Up to 24	3 x 40 mL	VOA Vial w/HCL	8260B (VOC)	14 days	STL Houston	1 event/ building
Well Headspace	6	400 mL*	Summa*	TO-15* (VOCs)/SF6	14 days	Columbia Analytical*	1 event/ building
Soil Gas	24	400 mL*	Summa*	TO-15* (VOCs)/SF6	14 days	Columbia Analytical*	1 event/ building
Sub-slab Gas	3	400 mL*	Summa*	TO-15* (VOCs)/SF6	14 days	Columbia Analytical*	1 event/ building
Indoor Air	3	6 L*	Summa*	TO-15 SIM* (VOC)	14 days	Columbia Analytical*	1 event/ building
Indoor Air Tracer	6	250 mL	Tedlar Bag	SF_6	3 days	Columbia Analytical*	1 event/ building
Ambient	3	6 L*	Summa*	TO-15 SIM* (VOCs)	14 days	Columbia Analytical*	1 event/ building
Ambient Radon	2	100 mL	Evacuated canister	Mathieu, 1998 (Radon)	3 days	University Southern California	1 event/ building
Indoor Air Radon	3	100 mL	Evacuated canister	Mathieu, 1998 (Radon)	3 days	University Southern California	1 event/ building
Sub-slab Radon	3	100 mL	Evacuated canister	Mathieu, 1998 (Radon)	3 days	University Southern California	1 event/ building

Note: 1) * = For the initial sampling event at each demonstration building, some VOC analyses were conducted by H&P Mobile Geochemistry using an on-site mobile laboratory. For these analyses, 50 mL samples were collected using 60 mL gas tight syringes. 2) Number of samples does not include additional samples collected for QA/QC. 3) Geotechnical samples and vadose zone permeability testing not included.

Experimental Controls: Quality control samples were collected during each sampling event to ensure that comparable data were collected throughout the study. For each type of sample, a minimum of 1 field duplicate was collected for every 20 samples and for each sampling event. In addition, field blank samples were collected for the water analyses. The collection and analysis of quality control samples are fully described in the QAPP, included as Appendix B.

Data Quality Parameters: Measures to ensure representativeness, completeness, comparability, and precision of the data are described in the QAPP, included as Appendix B.

Data Quality Indicators: Specific data quality criteria for representativeness, completeness, comparability, and precision of the data and the associated evaluation methods are described in the QAPP, included as Appendix B.

Calibration Procedures, Quality Control Checks, and Corrective Action: Laboratory quality control procedures are described in the QAPP, included as Appendix B.

3.5.8 Demobilization

This investigation utilized permanent monitoring points for the collection of all subsurface samples. These sampling points were left in place following project completion in order to allow for their use in potential follow-up studies. As a result, no demobilization was required. Authorization to leave the sampling points in place was obtained from the respective site managers.

3.6 Selection of Analytical/Testing Methods

Traditional methods for the analysis of soil and groundwater were implemented in this investigation. All of the laboratory methods selected represent standard methods developed by the EPA, ASTM, or American Petroleum Institute (API). These methods have been thoroughly validated and widely applied at corrective action sites, providing a high level of assurance in their ability to provide accurate results.

Groundwater samples were analyzed by EPA method 8260 for quantification of specific volatile organic compounds.

During the initial investigation at each site, air and soil gas samples were screened by EPA method 8021 (direct GC) using an on-site mobile laboratory, and further analyzed by EPA method 8260B. This two-tiered analysis procedure allowed for efficient utilization of the on-site mobile laboratory while still providing accurate quantification of both high concentration and low concentration samples. During the subsequent sampling events at both sites, indoor and ambient samples were analyzed by the TO-15 SIM method (low level) for a select list of compounds, all other vapor samples were analyzed by the standard TO-15 method. Gas samples requiring SF_6 analysis were analyzed using a modified NIOSH 6602 method which utilizes a gas chromatograph (GC) with an electron capture detector (ECD).

Soil samples were analyzed for geotechnical parameters by ASTM and API methods (ASTM D2216 and API 40). Geotechnical parameters selected for analysis include bulk density, fraction organic carbon, porosity, permeability to water, and hydraulic conductivity.

Radon gas samples were collected in vacuum cells or Tedlar bags for radon analysis, and were analyzed using the extraction method of Berelson, 1987 and the analysis method of Mathieu, 1998 at the University of Southern California. Additional radon samples collected by means of pre-weighed activated carbon canisters were analyzed using EPA Method #402-R-93-004 079 and had a method detection limit of 0.4 pCi/L.

3.7 Selection of Analytical/Testing Laboratory

Laboratories were selected for their abilities to meet the data quality objectives of the investigation as detailed in the QAPP, Appendix B. PTS Laboratories, Inc., in Houston, Texas, is a full-service core analysis laboratory that provides basic and advanced engineering data used to characterize and remediate sites throughout the United States and around the world. PTS analyzes soil cores for physical properties, geotechnical soil parameters, and free product mobility indicators. Severn Trent Laboratory (STL) in Houston, Texas, is an environmental laboratory with testing capabilities that include chemical, physical, and biological analyses of water, wastewater, solid waste, soil, sludge, and air. Microbiologic and air toxics testing are also available. STL Houston is certified/qualified in six states and is approved by the National Environmental Laboratory Accreditation Program (NELAP) and the U.S. Army Corps of Engineers' Hazardous, Toxic, and Radioactive Waste Program. Groundwater Services has utilized both STL and PTS on numerous previous projects on which they have established a performance history of achieving the required project data quality objectives.

H&P Mobile Geochemistry was selected because of their on-site analytical capabilities and familiarity with vapor intrusion investigations.

Columbia Analytical Services Inc. (CAS) is an environmental laboratory that is oriented towards vapor analysis. CAS has demonstrated proficiency in meeting the requirements of DOD programs in previous vapor intrusion investigations and offers low detection limits while remaining cost effective.

No commercial laboratories were identified that could analyze gas samples for radon. Radon gas samples were analyzed by Dr. Doug Hammond at the University of Southern California Department of Earth Sciences. The investigators greatly benefited from Dr. Hammond's knowledge of radon analysis and his expertise in radon sample collection. Additional radon samples were collected during several events using passive radon samplers consisting of activated carbon. These samplers were provided and analyzed by Accustar Labs, Medway, Massachusetts.

The following laboratories were used for analysis of site investigation samples:

> Severn Trent Laboratory, Inc., 6310 Rothway Street, Houston, Texas 77040
> Used for analysis of groundwater samples by USEPA Method 8260.
>
> PTS Laboratories, Inc., 4342 West 12th, Houston, Texas 77055
> Used for geotechnical analysis of soil samples.
>
> H&P Mobile Geochemistry, 148 S. Vinewoood Street, Escondido, California 92127
> Fixed lab certification No. 1561, Mobile lab certification No. 2278

H&P provided a mobile laboratory for on-site analysis of vapor samples by USEPA Methods 8021 and TO-15.

Columbia Analytical Services, 2655 Park Center Dr., Ste. A, Simi Valley, CA 93065
Used for analysis of vapor samples by USEPA Methods TO-15, TO-15 SIM, and NIOSH 6602 for SF_6.

Dr. Doug Hammond, Earth Sciences USC, ZHS 117, 3651 Trousdale Parkway, Los Angeles, CA 90089
Used for analysis of radon samples.

Accustar Laboratory, 11 Awl Street, PO Box 158, Medway, MA 02053.
Used for analysis of passive radon samplers.

4. Performance Assessment

4.1 Performance Criteria

The primary objective of this demonstration study was to identify and validate the limited set of site investigation samples that provides the most accurate and reliable evaluation of vapor intrusion at corrective action sites. This objective is met by:

1) Collecting a high density of data related to vapor intrusion at the test site,
2) Analyzing this data to obtain a thorough understanding of vapor intrusion processes at the test site, and
3) Utilizing the results to develop a reliable and cost-effective approach for investigation of vapor intrusion at other sites.

The specific performance criteria utilized in this process are provided in Table 4.1.1. The primary performance criteria reflect the project performance objectives while the secondary performance objectives reflect the intermediate data evaluation results that support the project objectives. Performance confirmation methods and data evaluation methods are discussed in sections 4.2 and 4.3, respectively.

Table 4.1.1: Performance Criteria

Performance Criteria	Description	Primary or Secondary
Collection of Data Representative of Site Conditions.	Precision, Accuracy, Completeness, Representativeness, and Comparability as defined in Table 4.2 and Appendix B.	Primary (See Section 4.3)
Vapor Intrusion Impact	Determine presence or absence of vapor intrusion impact at test site. Vapor intrusion impact defined as indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources.	Primary (See Section 4.4.1)
Reliable Vapor Intrusion Investigation Approach	Identify a limited site investigation program that will provide a reliable indication of vapor intrusion impacts.	Primary (See Section 4.6)
Movement of VOCs Across Key Interfaces	Identify environmental interfaces (e.g., GW-soil gas interface, soil vadose zone, building foundation) along the vapor intrusion pathway which have the greatest influence on the extent of vapor intrusion. Evaluate mass flux of VOCs across these interfaces to understand influence on vapor intrusion.	Secondary (See Section 4.4.2)
Site Physical Characteristics	Determine impact of site characteristics on vapor intrusion.	Secondary (See Section 4.4.5)
Spatial and Temporal Variability in VOC Concentration	Identify environmental media with lowest and highest temporal and spatial variability in VOC concentrations. Low variability indicates that media can be characterized with fewer samples. High variability indicates that media can be well characterized only with a larger number of samples.	Secondary (See Section 4.4.3)
Attenuation Factors	Evaluate utility of attenuation factors for screening of vapor intrusion. Attenuation factors describe the change in concentration of COC between and within environmental media.	Secondary (See Section 4.4.4)

4.2 Performance Confirmation Methods

For this project, performance confirmation consists of two parts: i) collection of site data that is representative of actual site conditions (i.e., data quality criteria) and ii) data analysis, evaluation, and interpretation to satisfy the technology performance criteria listed in Tables 4.1.1 and 4.2.1. Performance confirmation with respect to the data quality criteria is addressed in Section 4.3 while performance confirmation with respect to the technology performance criteria is addressed in Section 4.4.

The collection of site data that was representative of actual site conditions was achieved through compliance with the QAPP, included as Appendix B. The QAPP details the sampling and

analysis procedures that were utilized for each type of sample collected for the data collection portion of the project. In addition, the QAPP defines quality assurance objectives for precision, accuracy, completeness, representativeness, and, comparability that was used to quantitatively evaluate the quality of the data obtained.

Table 4.2.1: Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Performance Criteria for Data Quality Assurance (Quantitative)			
Precision	+/- 30% relative percent difference (RPD)	1 duplicate per 20 samples for all VOC analyses (water and air/gas)	RPD goal met in 82% of duplicate pairs.
Accuracy	Field blanks below PQLs. Laboratory accuracy as defined in Appendix B, Tables 2.2 and 2.3.	All VOC analyses (water and air/gas)	Goal achieved in 98% of field blanks and laboratory QA/QC samples.
Completeness	> 90% valid field samples. >95% valid laboratory results.	All VOC analyses (water and air/gas)	Achieved
Performance Criteria for Data Quality Assurance (Qualitative)			
Representativeness	Use of field sampling procedures, laboratory analytical procedures, sample holding times, etc. defined in QAPP.	All field samples	Goal achieved for 99% of samples.
Comparability	Use of standard and consistent sampling and analysis procedures for all samples, as defined in QAPP.	All field samples	Goal achieved for 99% of samples.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Performance Criteria for Technology Demonstration (Qualitative and Quantitative)			
Vapor Intrusion Impact	Presence or absence of vapor intrusion impact at test site. Vapor intrusion impact defined as indoor air concentration of COC above risk-based screening limit and not attributable to background indoor air sources.	Detection of VOC in indoor air at concentrations exceeding EPA, 2002 indoor air screening limits. If limits exceeded, evaluation of sub-slab and indoor air data to separate vapor intrusion from background indoor air sources as described in Section 4.3 of Demonstration Plan.	Evaluation of indoor, ambient, and sub-slab VOC and radon concentrations indicated an absence of vapor intrusion impacts above applicable regulatory limits in all three of the demonstration buildings during each of the sampling events. Application of the same investigation approach at other buildings would be expected to yield definitive results concerning the presence or absence of a vapor intrusion impact (see Section 4.4.1).
Movement of VOCs Across Key Interfaces	Calculation of mass flux across key vapor intrusion pathway interfaces, see Section 4.3 of Demonstration Plan.	Consistent or decreasing mass flux along the vapor intrusion pathway.	Calculated mass flux values had high uncertainty and did not show a consistently decreasing mass flux along the vapor intrusion pathway (See Section 4.4.2)

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Spatial and Temporal Variability in VOC Concentration	Calculation of spatial and temporal variability in chemical concentration for each environmental medium investigated	Statistical measures of variability as described in Section 4.3 of Demonstration Plan	High spatial and longer-term (months) temporal variability in subsurface VOC concentrations compared to above-ground VOC concentrations indicate that a larger number of samples are required to characterize subsurface media. Short-term temporal variability (days) does not appear to be a major source of uncertainty in vapor intrusion evaluations (see Section 4.4.3)
Attenuation Factors	Calculation of attenuation factors describing the attenuation of chemicals from various environmental media to indoor air.	Statistical measures of variability as described in Section 4.3 of Demonstration Plan.	Calculated attenuation factors had moderate to high uncertainty but were consistently below EPA default values for pathway screening. Measured sub-slab to indoor air attenuation factors ranged from 3.8×10^{-4} to 7.6×10^{-3} compared to the current USEPA default value of 1.0×10^{-1} and the proposed value of 5.0×10^{-2}. Measured groundwater to indoor air attenuation factors ranged from 2.9×10^{-6} to 3.6×10^{-4} compared to the current EPA default value of 1.0×10^{-3} (the EPA has not proposed to change this default value). See Section 4.4.4

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual (Post Demo)
Site Physical Characteristics	Measurement of site soil characteristics and other physical characteristics of the site	Correlation of site characteristics to VOC distributions and fluxes as described in Section 4.3 of Demonstration Plan	Data set did not show expected correlation between lower soil permeability and higher VOC attenuation (See Section 4.4.5)
Reliable Vapor Intrusion Investigation Approach	Identification a limited site investigation program that will provide a reliable indication of vapor intrusion impacts	Statistical comparison of accuracy of vapor intrusion impact predicted by limited subset of site data compared to full set of data obtained for the site, as described in Section 4.3 of Demonstration Plan	We have developed a recommended approach for the reliable investigation of vapor intrusion. (See Section 4.6)

4.3 Evaluation of Data Quality

For the purpose of the data usability evaluation, analytical results were evaluated in groups: i) custody procedures, holding time, arrival temperatures, ii) sampling procedures and field instrumentation, iii) precision assessment, iv) accuracy assessment, and v) completeness assessment. A summary data usability evaluation for this project is presented below.

4.3.1 Custody Procedures, Holding Time, Arrival Temperatures

All samples submitted for analysis were received within required holding times and within the limits specified for temperature (groundwater samples only) with the exception of one set of groundwater samples received at 0.9°C (below target temperature range). All samples were submitted under chain of custody control with no indication of any losses of custody. On one occasion a groundwater sample was erroneously indicated on the COC and on another occasion a trip blank was not included in a groundwater sample shipment. In one instance a radon sample collected in a Tedlar bag was received empty, apparently due to an unnoticed perforation in the sample bag. Chain of custody documentation was provided by the final recipient of the samples to document the complete series of custody transactions.

Finding: *Based on the evaluation of custody procedures, holding time, and arrival temperature, no data quality issues were identified for 99% of the project samples. For 1% of the samples, data quality issues were identified but the data was determined to be usable. No data was rejected or not obtained based on custody procedures, holding time, or arrival temperatures.*

4.3.2 Sampling Procedures and Field Instrumentation

Sampling Procedures: All field instruments used for data collection were operated in accordance with the operating instructions, including required zero adjustment and calibration, when applicable. With the exception of groundwater samples collected from MW-3 and MW-10 during the July 2006 Altus event and MW-1 and MW-3 during the December 2006 Altus event, all samples for laboratory analysis were collected in accordance with commonly used procedures or sample collection methods validated during the previous field programs. Samples collected from the aforementioned monitoring wells were obtained prior to purging the wells due to the lack of recovery of groundwater in these wells following purging. In one instance a soil gas sample was not collected due to sample not being drawn into the summa canister (SS-2 from Altus December 2006 sample event). It is unclear whether this issue is related to a deficiency in sampling procedure or a faulty sample container, however, a duplicate sample was collected from this location for this sample event and yielded a valid sample.

Finding: *Based on the evaluation of sampling procedures and field instrumentation, no data quality issues were identified for 99% of the project samples. For 1% of the samples, data quality issues were identified but the data was determined to be usable. No data was rejected or not obtained based on custody procedures, holding time, or arrival temperatures.*

Sample Point Integrity: For subsurface sample points completed adjacent to (rather than under) the demonstration buildings, a leak tracer compound was used to evaluate sample point integrity. Various leak tracer compounds were used (pentane, sulfur hexafluoride [SF_6], 1,1-difluoroethane [1,1-dfa]) depending on the analytical method being used. Prior to sample collection, a paper towel saturated with pentane or 1,1-dfa, or a line attached to a cylinder of 100% SF_6, was placed within the sample point vault, which was covered by cardboard. As a result, any air entering the sample through leaks in the sample lines or leaks around the sample point casing, would introduce the tracer gas into the sample.

All samples collected from these sample points were found to contain detectable concentrations of leak tracer compounds, however, other researchers also report commonly finding low concentrations of leak compounds in subsurface samples (Personal communication from Matt Lavis of Shell and Todd McAlary of Geosyntec). In order to evaluate the significance of the leak tracer in the subsurface samples, the size of the leak was estimated as follows:

1) The concentration of leak tracer in the sample vault was not directly measured, but was conservatively assumed to be ≥5%. (A sample vault volume of 1000 mL and a release rate of 300 mL/min for 0.5 minutes with no escape to the atmosphere would yield an SF_6 concentration of 150/1000 or 15%.) As a result, any gas entering the sample through a leak was assumed to contain 5% leak tracer compound by volume.

2) For sulfur hexafluoride, a concentration of 5% by volume is 50,000 ppmv. As a result, the detection of more than 500 ppmv SF_6 (i.e., 0.05% leak tracer by volume) in a sample would indicate a potential leak in the sample point or line of greater than 1% of the sample volume.

3) For 1,1-difluoroethane, a concentration of 5% by volume is 135,000,000 ug/m^3. As a result, the fraction of sample volume originating through a leak was estimated by dividing the 1,1-difluoroethane concentration in the sample by 135,000,000 ug/m^3. The detection of more than 1,350,000 ug/m^3 1,1-difluoroethane (i.e., 0.05% leak tracer by volume) in a sample would indicate a potential leak in the sample point or sample line of greater than 1% of the sample volume.

The percent leakage for each sample was calculated and evaluated to determine if the leak should be considered potentially significant. Due to a change in analytical procedures, the use of 1,1-dfa during the second event at Hill AFB resulted in elevated detection limits that prevented useful quantitation of the COC of interest. This issue is addressed in Section 4.3.6. Sulfur hexafluoride was used as a leak tracer in subsequent investigations because elevated concentrations of this compound do not interfere with the TO-15 analysis.

Using the evaluation procedure described above, sample point leakage was estimated to be less than 1% for the majority of subsurface gas samples. For a small number of samples, the leakage was greater than 1% but less than 10% (See Table 4.3.2). These samples were considered valid because the expected error in measured VOC concentration associated with the leakage is also expected to be less than 10%. For later sample events, a fresh bentonite seal was applied around the top of the sample point prior to sample collection to minimize leakage. This approach resulted in a reduction in the leak tracer concentration in subsequent samples.

Table 4.3.2: Data Quality Issues Associated With Sample Point Integrity

Issue	Samples Affected	Corrective Actions
Sample point leak tracer 1,1-dfa in samples causes elevated detection limits for target VOCs	March 2006 sampling event at Hill AFB, soil gas samples: Residence #1 SG-1, SG-3, SG-4, SG-9, SG-10, SG-11, SG-12. Residence #2 SG-1, SG-2, SG-10, SG-11, SG-12	Use SF6 as leak tracer for future sample events Apply seal of fresh bentonite around top of sample point prior to collection
Leak tracer concentration indicates leakage of 1% to 10% by volume. (Note, samples did not meet DQO for leakage of less than 1%, but results still considered reliable based on leakage of less than 10%)	March 2006 sampling event at Hill AFB, soil gas samples: Residence #1 SG-1, SG-3, SG-9, SG-10, SG-11. Residence #2 SG-1, SG-10, SG-11, SG-12. July 2006 sampling event at Altus AFB, SG-4, MW-4 (headspace), MW-6 (headspace). December 2006 sampling event at Altus AFB, SG-4 and MW-4 (headspace)	Apply seal of fresh bentonite around top of sample point prior to collection

***<u>Finding</u>**: Based on the evaluation of samples for acceptable accuracy, no data quality issues were identified for 98% of the project samples. For 2% of the samples, data quality issues were identified but the data was determined to be usable, and for 0.4% of the samples the data was rejected or not obtained.*

4.3.3 Precision Assessment: Duplicate Samples, Matrix Spike and Matrix Spike Duplicate

The objectives for field precision and laboratory precision were defined in Section 3.1 of the QAPP, included as Appendix B of this report. All duplicate samples were labeled in a manner to avoid revealing the duplicate sample pairing to the laboratory. The results of the data evaluation based on these objectives are provided below.

<u>Field Precision</u>: The requirement for a minimum of one pair of duplicates per ten samples collected was met for all samples collected with one exception. Sampling precision for all analyses is demonstrated by field duplicates meeting the DQO requirement of ≤30% relative percent difference (RPD) between duplicate samples. This objective was achieved in the majority (>80%) of samples analyzed. Exceedance of the RPD goal was most commonly associated with low concentration samples.

<u>Analytical Detection Limits</u>: The original project QAPP specified reporting limits of 2 to 5 ug/m^3 for target VOCs analyzed by 8260 SIM (Mobile Lab) or TO-15 (fixed lab) for both above-ground and subsurface gas samples. However, the predominance of non-detect results (with detection limits above the EPA screening levels) for indoor and ambient samples from the first field program (Altus AFB) made it difficult to evaluate the presence or absence of vapor intrusion impacts in the demonstration building. As a result, we elected to utilize TO-15 SIM to achieve lower detection limits for all indoor

and ambient samples collected during subsequent field events. For many regulatory purposes, non-detect results at standard TO-15 detection limits are sufficient to demonstrate an absence of vapor intrusion impacts. For example, New Jersey indoor screening levels have a floor of 0.5 ppbv (1-5 ug/m^3) based on typical TO-15 reporting limits (NJDEP 2006). As a result, the decision to use TO-15 or TO-15 SIM for analysis of indoor samples should be made based on a consideration of regulatory and other requirements.

The DQO for analytical detection limits were achieved for all samples with two exceptions. In one instance the presence of naturally-occurring pinene at a sample cluster at Altus AFB elevated analytical detection limits above the DQO for 2 soil gas samples. This soil gas cluster is located between two pine trees, which are believed to be the source of the pinene. Pinene was also observed in samples from this soil gas cluster during the first sampling event conducted at Altus AFB in March 2005. During the second sampling event conducted at Hill AFB, elevated concentrations of the leak tracer 1,1-dfa required significant sample dilutions and resulted in elevated detection limits for several TO-15 soil gas samples.

Laboratory Precision: Laboratory precision of groundwater samples was demonstrated by acceptable RPD calculated for MS/MSD samples. Groundwater MS/MSD samples were collected during each sampling event and were deemed acceptable. Laboratory precision of method TO-15 SIM and TO-15 was demonstrated by acceptable RPD of samples analyzed as duplicates at the laboratory (not field collected). Acceptable precision is obtained for both the laboratory analysis and field sampling if the results of the samples are within the RPD limits specified by the QAPP. Laboratory precision was generally acceptable with one notable exception occurring during the first sampling event at Altus AFB.

During the first Altus sampling event, poor laboratory precision, detection of unexpected VOC, and other data irregularities lead to the conclusion that the Summa canisters used for sample collection were impacted by carry-over contamination from a previous sampling event. The laboratory batch certification (i.e., testing on one canister per batch of 20 to verify cleaning procedures) had failed to detect this residual contamination. Based on this experience, individual clean certification (at an additional cost of $75/sample) was requested for all subsequent Summa canisters. For two subsequent field sampling events, the shipment of Summa canisters from the laboratory was delayed due to difficulties achieving the individual clean certification. This experience further highlights the difficulties laboratories can have completely eliminating carry-over contamination in Summa canisters between sampling events. The invalidation of the Summa canister results from the first field event had a minimal impact on the project because the Summa canister samples were duplicates of those analyzed using the on-site mobile laboratory.

Finding: *Based on the evaluation of samples for acceptable precision, no data quality issues were identified for 82% of the project samples. For 13% of the samples, data quality issues were identified but the data was determined to be usable, and for 5% of the samples the data was rejected or not obtained.*

4.3.4 Accuracy Assessment: Blank Analysis, Laboratory Control Standards, Surrogate Recovery

The objectives for field accuracy and laboratory accuracy were defined in Section 3.2 of the QAPP, included as Appendix B of this report. The results of the data evaluation based on these objectives are provided below.

Field Accuracy: Field accuracy was evaluated based on use of trip blanks, field blanks, and adherence to all method specified sample handling, preservation, and holding times. Trip blanks were utilized for groundwater samples, and occasionally for gas samples. The TO-15 trip blank sample submitted during the first sampling event at Altus AFB indicated a contamination issue with the TO-15 sample containers (mini-summas) resulting in the rejection of TO-15 data for this sampling event. Field blanks were collected for groundwater samples, while ambient samples collected for VOC and radon analyses were utilized as field blank samples for QA purposes.

The DQO for field accuracy of groundwater samples were satisfied based on the trip blanks and field blanks submitted for analysis. The field blanks collected during the groundwater sampling events were frequently found to contain very low concentrations of water disinfection byproducts. The presence of these compounds may be due to the use of commercially purchased distilled water that was used during the field program instead of reagent grade deionized water. In one case, toluene was detected in the field blank at a concentration consistent with equilibrium partitioning of the toluene concentration observed in ambient air at the site.

Laboratory Accuracy: Laboratory control samples analyzed by methods TO-15 and TO-15 SIM were acceptable based on information provided by the laboratory and the absence of any exception reports associated with the data. Laboratory control samples analyzed by method 8260B (groundwater) were found to be acceptable with no DQO exceedances for any constituents of interest. No other analytical methods utilized LCS samples for demonstration of accuracy.

Surrogate recoveries in all applicable analysis methods were acceptable with the exception of several VOC analyses conducted by the mobile laboratory during the initial event at Hill AFB. For the affected samples, duplicate or companion samples analyzed by a different method were found to be acceptable.

All laboratory blanks analyzed as part of laboratory QA procedures for groundwater analysis and TO-15/TO-15 SIM analysis were acceptable i.e., no compounds were detected at concentrations greater than the detection limits.

4.3.5 Completeness Assessment

For each sampling event, a completeness assessment was conducted to evaluate whether all necessary analytical samples were collected and usable data was generated. With the exception of the previously mentioned QC samples, all necessary analytical samples were collected for this investigation. Table 4.3.5.1 summarizes results of the data quality/usability evaluation presented in the preceding sections.

Finding: *The established goals for data completeness were achieved.*

Table 4.3.5.1: Summary of Data Evaluation Results.

Data Quality Objective	Results of Data Quality Evaluation			
	Meets Data Objectives	Other Useable Data	Rejected Data	Comments
Custody, Hold, Temperature	99%	1%	0%	
Sampling, Instruments	99%	1%	0%	
Accuracy Assessment	82%	13%	5%	Rejected TO-15 data and elevated detection limits.
Precision Assessment	98%	2%	0.4%	
Completeness Assessment	100%	0%	0%	

Note: Percentages based on Total number of samples collected (675) including all QA/QC and mobile laboratory data, exclusive of purge study data.

4.3.6 Responses to Identified Data Quality Issues

After each sampling event, remedial measures were implemented to address identified data quality issues. Key data quality issues and responses are summarized below.

<u>Sample Point Leakage</u>: The presence of elevated leak tracer concentrations in soil gas and well headspace samples indicated that significant leakage occurred during the collection of these samples.

Response: In order to address the problems associated with leaks around the sample point casing, we applied an additional temporary bentonite seal around the top of each soil gas sampling point and monitoring well point immediately prior to sample collection. This response action significantly reduced the problem of sample point leakage.

Sample Point Leak Tracer: The leak tracer compound 1,1-Difluoroethane was used as a leak indicator for the collection of gas samples from subsurface sampling points installed adjacent to the demonstration buildings during the second Hill AFB sampling event. Unfortunately, high concentrations of 1,1-difluoroethane resulted in elevated detection limits for target VOCs in 12 of 16 soil gas points where the leak tracer was used. Columbia Analytical reports that the high concentrations of 1,1-difluoroethane interfered with the detector on the mass spectrometer so that no VOC could be quantified when these samples were analyzed without dilution. As a result, we were not able to evaluate the presence or absence of low concentrations of target VOC in these samples. The leaks were most likely associated with the sample points rather than the sample lines because none of the six well headspace samples collected using the same sample train were found to contain elevated levels of leak compound.

Response: In order to address the problems associated with leak tracer in samples, the following changes were implemented for future collection of soil gas point samples. In addition to an additional bentonite seal, SF_6 was used as a leak tracer compound. Columbia Analytical reports that high concentrations of SF_6 in the soil gas samples would not result in elevated detection limits for the target VOC. The use of SF_6 as the leak tracer eliminated the problem of analytical interference.

Initial Altus AFB TO-15 Data: In addition to on-site analysis by 8260B, a sub-set of samples was collected in duplicate for off-site analysis of VOC by TO-15. The trip blank sample that accompanied the summa canisters was found to contain several VOC at concentrations that exceeded the reporting limits established in the QAPP. In addition, all of the samples were found to contain detectable levels of VOC which were not expected to be present at the site (e.g., acetone and trimethylbenzene). Finally, VOC concentrations were found to differ significantly between field duplicate samples (i.e., RPD >30%). Based on the data quality evaluation, it appears that the summa canisters were not properly cleaned prior to use for this demonstration and, as a result, the TO-15 analytical results were not useable.

Response: For subsequent sample events, all summa canisters were individually certified clean by the laboratory prior to use.

In addition to the above mentioned issues, additional QA/QC procedures were implemented and refined as the project progressed. For example, DQO were established for radon, an analytical parameter not included in the original demonstration plan or QAPP.

4.4 Data Analysis, Interpretation and Evaluation

Based on the site investigations conducted prior to this demonstration (See Section 3.3), PCE and TCE are the primary VOC associated with the groundwater plume underlying the test building at Altus AFB and TCE is the primary VOC associated with groundwater under the demonstration

buildings at Hill AFB. Based on these previous results and a review of the data set collected for the demonstration, TCE and PCE were identified as the key site constituents at Altus AFB and TCE was identified as the key site constituent at Hill AFB. As a result, the analyses presented in Section 4.4 focuses on these constituents.

4.4.1 Vapor Intrusion Impact

Determination of the presence or absence of a vapor intrusion impact at the demonstration building is a primary performance criterion for the demonstration project. A vapor intrusion impact was defined as an exceedance of applicable indoor air VOC concentration screening values attributable to vapor intrusion. For each demonstration building, multiple lines of evidence have been used to evaluate the presence or absence of a vapor intrusion impact. For Altus AFB, we have used the EPA indoor air screening values for a 10^{-4} to 10^{-6} risk range from EPA, 2002 as the applicable indoor VOC limits (i.e., 0.0022 to 0.22 ug/m^3 for TCE and 0.81 to 81 ug/m^3 for PCE). For Hill AFB, we have used the base-specific residential indoor air action level as the applicable limit. The Hill AFB residential indoor air action level (2.3 ug/m^3) is based on typical indoor background concentrations (MWH_Americas 2004).

Measured Indoor VOC Concentrations

The indoor VOC concentration can directly show the absence of a vapor intrusion impact (at the time of sample collection) if VOC concentrations are below applicable regulatory or risk limits. However, if the concentration of one or more VOC is above the applicable limit, additional evaluation is required to determine if the source of the impact is vapor intrusion.

Building 418, Altus AFB: During the first sampling event, analytical detection limits were not sufficient to directly evaluate the presence or absence of a vapor intrusion impact. During subsequent sampling, TO-15 SIM was used for all indoor and ambient samples to provide lower analytical detection limits. During the follow-up sampling events, the TCE concentrations in Building 418 were above or within the USEPA indoor air concentration limit for a 10^{-4} to 10^{-6} risk range (2.2 to 0.022 ug/m^3), but these concentrations were similar to concentrations in ambient air. In contrast, the PCE concentrations in Building 418 were consistently approximately twice ambient concentrations, but below the EPA indoor air concentration limit for 10^{-6} risk (0.81 ug/m^3). For all of the sampling events, neither the PCE nor TCE concentrations in indoor air were statistically different from the concentration in ambient air. However, during the December 2006 event the difference approached significance for both TCE and PCE (p = 0.06 and 0.07, respectively, based on a two-sided t-test). Average concentrations are shown on Table 4.4.1.1.

Table 4.4.1.1: Measured Indoor and Ambient VOC Concentration: Altus AFB.

Test Period	Avg. Indoor Concentration (ug/m^3)		Avg. Ambient Concentration (ug/m^3)	
	TCE	PCE	TCE	PCE
March 2005	<5	<5	<5	<5
July 2006	9.45 +/- 2.21	0.26 +/- 0.060	12.3 +/- 5.74	0.12 +/- 0.035
December 2006	0.13 +/- 0.042	0.42 +/- 0.17	0.063 +/- 0.021	0.17 +/- 0.038

Note: Values shown are mean +/- standard deviation. For ambient PCE conc. July 06, non-detect result with elevated detection limit (0.52 ug/m^3) not included in calculation.

Residence #1, Hill AFB: During both sampling events, both the average and maximum indoor TCE concentrations were below the action level established for Hill AFB (2.3 ug/m^3) and were similar to ambient air TCE concentrations. The differences between indoor and ambient TCE concentrations were not statistically significant. Average concentrations are shown on Table 4.4.1.2.

Residence #2, Hill AFB: During both sampling events, both the average and maximum indoor TCE concentrations were below the action level established for Hill AFB (2.3 ug/m^3). For the March 2006 sample event, the indoor TCE concentration was significantly above the ambient TCE concentration ($p = 0.03$ based on a two-sided t-test). Average concentrations are shown on Table 4.4.1.2.

Table 4.4.1.2: Measured Indoor and Ambient TCE Concentration: Hill AFB.

Test Period	Avg. Indoor Concentration (ug/m^3)	Avg. Ambient Concentration (ug/m^3)
Residence #1		
August 2005	0.059 +/- 0.006	0.063 +/- 0.027
March 2006 Baseline	0.075 +/- 0.016	0.092 +/- 0.085
Residence #2		
August 2005	0.062 +/- 0.013	<0.046
March 2006	0.14 +/- 0.044	0.055 +/- 0.017

Note: Values shown are mean +/- standard deviation.

Evaluation of Uncertainty: The uncertainty in measured indoor and ambient VOC concentrations was low. The standard deviation for each set of three samples was typically less than 50% of the mean. Assuming a normal distribution, the 95% confidence interval for the mean of three samples is approximately 1.7 times the standard deviation. (i.e., For three samples, 95% confidence interval = mean +/- 2.92 x std. dev. / sq. root of 3.)

Finding: *For Residence #1 and #2 at Hill AFB, the TCE concentration in indoor air was well below the action level for both sampling events indicating no vapor intrusion impacts at these times. For Building 418 at Altus AFB, the evaluation of VOC concentrations in indoor air did not provide a definitive indication of the presence or*

absence of a vapor intrusion impact because the TCE concentration was above or within the EPA risk range, but similar to ambient concentrations.

Estimated Indoor VOC Concentrations Attributable to Vapor Intrusion

Because the measured indoor VOC concentrations in the demonstration buildings were similar to measured ambient concentrations, and consistent with typical indoor background concentrations, it is possible that none of the measured VOC concentrations are attributable to vapor intrusion. In order to evaluate the potential contribution of vapor intrusion to the measured indoor VOC concentration, radon has been used as a tracer for the movement of soil gas through the building foundation. Radon is a naturally occurring gas present in all soils. Because there are no common indoor sources for radon other than soil gas and ambient air, radon can be used as an additional tool to understand the potential sources of VOC detected in indoor air.

At all three demonstration buildings, the indoor radon concentration was greater than the ambient radon concentration during the sample events for which ambient radon concentration was measured (see Table 4.4.1.3). However, because only one or two ambient radon samples were collected for these events, we could not make a statistical comparison between indoor and ambient radon concentrations. The observed difference between indoor and ambient radon concentrations suggests that some migration of soil gas through the building foundation is occurring at all three buildings. At the Altus AFB, the radon attenuation factor was similar during all three sampling events. In contrast, at the Hill AFB residences, less attenuation (i.e., higher attenuation factors) was observed during the March 2006 sample event compared to the August 2005 sample event. Example attenuation factor calculations are shown in Appendix E.

Table 4.4.1.3: Sub-slab to Indoor Air Attenuation Factor: Radon.

Test Period	Avg. Sub-Slab Conc. (pCi/L)	Average Indoor Conc. (pCi/L)	Avg. Ambient Conc. (pCi/L)	Attenuation Factor
Building 418, Altus AFB				
March 2005	843 +/- 322	<0.4	NM	4.8×10^{-4}*
July 2006	573 +/- 42	0.35 +/- 0.09	0.13	3.8×10^{-4} +/- 1.1×10^{-4}
December 2006	702 +/- 441	0.83 +/- 0.16	0.30	7.6×10^{-4} +/- 4.9×10^{-4}
Residence #1, Hill AFB				
August 2005	450 +/- 341	0.32 +/- 0.16	NM	7.3×10^{-4}*
March 2006	68 +/- 54	0.61 +/- 0.20	0.095	7.6×10^{-3} +/- 6.5×10^{-3}
Residence #2, Hill AFB				
August 2005	409 +/- 362	0.38 +/- 0.04	NM	9.2×10^{-4}*
March 2006	427 +/- 283	0.80 +/- 0.01	0.095	1.7×10^{-3} +/- 1.1×10^{-3}

Note: Values shown are mean +/- standard deviation. NM = Ambient radon concentration not measured during March 2005 or August 2005 sampling events. * = Upper-bound estimate based on measured indoor radon concentration without correction for radon concentration in ambient air.

As shown in Table 4.4.1.4, the sub-slab to indoor air attenuation factors for TCE and PCE were similar to the radon attenuation factors with the exception of the TCE

attenuation factor for the December 2006 sample event (Altus AFB) which was four times higher than the radon attenuation factor (0.0033 versus 0.00076). This result suggests a potential indoor source of TCE during this sample event. However, we were unable to calculate VOC attenuation factors for 6 of 10 paired sub-slab and indoor air measurements due to either (1) non-detect results in indoor air, (2) ambient concentrations greater than indoor concentrations, or (3) no VOC detections in sub-slab samples. In contrast, we were able to calculate radon attenuation factors for 4 of 4 paired sub-slab and indoor air measurements where we also measured ambient radon concentration. Thus, our results indicate that radon is a more sensitive tracer than VOC for the movement of soil gas through a building foundation.

Table 4.4.1.4: Sub-slab to Indoor Air Attenuation Factor: TCE & PCE.

Test Period	Avg. Sub-Slab Conc. (ug/m^3)	Average Indoor Conc. (ug/m^3)	Avg. Ambient Conc. (ug/m^3)	Attenuation Factor
TCE Building 418, Altus AFB				
March 2005	20.3 +/- 18.6	<5	<5	N/C (1)
July 2006	49.8 +/- 62.0	9.45 +/- 2.21	12.3 +/- 5.74	N/C (2)
December 2006	21.3 +/- 17.0	0.13 +/- 0.042	0.063 +/- 0.021	0.0033 +/- 0.0028
PCE Building 418, Altus AFB				
March 2005	58.5 +/- 59.4	<5	<5	N/C (1)
July 2006	402 +/- 501	0.26 +/- 0.060	0.12 +/- 0.035	3.5×10^{-4} +/- 4.3×10^{-4}
December 2006	348 +/- 283	0.42 +/- 0.17	0.17 +/- 0.038	7.2×10^{-4} +/- 6.6×10^{-4}
TCE Residence #1, Hill AFB				
August 2005	20.3 +/- 14.6	0.059 +/- 0.006	0.063 +/- 0.027	N/C (2)
March 2006	8.4 +/- 8.6	0.075 +/- 0.016	0.092 +/- 0.085	N/C (2)
TCE Residence #2, Hill AFB				
August 2005	15.0 +/- 17.3	0.062 +/- 0.013	<0.046	0.0011 +/- 0.0013
March 2006	<0.94	0.14 +/- 0.044	0.055 +/- 0.017	N/C (3)

Note: Values shown are mean +/- standard deviation. N/C = Not calculated due to: (1) non-detect results in indoor air, (2) ambient concentrations greater than indoor concentrations, or (3) no VOC detected in sub-slab samples. For ambient PCE conc. July 06, non-detect result with elevated detection limit (0.52 ug/m^3) not included in calculation.

To evaluate whether a VOC vapor intrusion impact has occurred, indoor air VOC concentrations attributable to VI have been estimated based on average sub-slab VOC concentrations and the slab attenuation measured for radon. The calculations are illustrated in Appendix E and the results are summarized in Table 4.4.1.5.

Table 4.4.1.5: Estimated VOC Conc. in Indoor Air Due to Vapor Intrusion.

Compound	**Average Sub-Slab Conc. (ug/m^3)**	**Estimated Indoor Conc. Due to Vapor Intrusion (ug/m^3)**	**Avg. Measured Indoor Air Conc. Minus Avg. Ambient Conc. (ug/m^3)**
TCE Building 418, Altus AFB			
March 2005	20.3 +/- 18.6	0.0096 +/- 0.010	N/C (1)
July 2006	49.8 +/- 62.0	0.019 +/- 0.025	N/C (2)
December 2006	21.3 +/- 17.0	0.016 +/- 0.017	0.070 +/- 0.047
PCE Building 418, Altus AFB			
March 2005	58.5 +/- 59.4	0.028 +/- 0.012	N/C (1)
July 2006	402 +/- 501	0.15 +/- 0.20	0.14 +/- 0.070
December 2006	348 +/- 283	0.26 +/- 0.27	0.25 +/- 0.18
TCE Residence #1, Hill AFB			
August 2005	20.3 +/- 14.6	0.015 +/- 0.015	N/C (2)
March 2006	8.4 +/- 8.6	0.082 +/- 0.10	N/C (2)
TCE Residence #2, Hill AFB			
August 2005	15.0 +/- 17.3	0.014 +/- 0.012	0.015 +/- 0.014
March 2006	<0.94	<0.0016	0.085 +/- 0.047

Note: N/C = Not calculated due to: (1) non-detect results in indoor air, (2) ambient concentrations greater than indoor concentrations, or (3) no VOC detected in sub-slab samples.

For five data sets (TCE in December 2006 Altus AFB; TCE in August 2005 and March 2006 for Hill AFB Residence #2; PCE in July 2006 and December 2006 Altus AFB), the average indoor air VOC concentration was greater than the average ambient VOC concentration, allowing for a comparison between the estimated indoor VOC concentration due to vapor intrusion and the measured indoor VOC concentration (corrected from ambient). For three of five data sets, the estimated indoor concentration due to vapor intrusion closely matched the measured concentration, suggesting that vapor intrusion was the primary source of the increase in indoor concentration relative to ambient. For the other two data sets (TCE in Building 418, December 2006 and TCE in Residence #2, March 2006), the estimated concentration due to vapor intrusion was less than the measured concentration corrected for ambient, suggesting a likely contribution from an indoor VOC source.

Building 418, Altus AFB: During all three sampling events, the estimated indoor TCE and PCE concentrations due to vapor intrusion were below the EPA screening levels for 10^{-6} risk (0.022 and 0.81 ug/m^3, respectively). This indicates an absence of a vapor intrusion impact during each of these sampling events.

Residence #1, Hill AFB: During both sampling events, the estimated indoor TCE concentration due to vapor intrusion was well below the Hill AFB action level (2.3 ug/m^3). This indicates the absence of a vapor intrusion impact during each of these sampling events.

Residence #2, Hill AFB: During both sampling events, the estimated indoor TCE concentration due to vapor intrusion was well below the Hill AFB action level (2.3 ug/m^3). This indicates the absence of a vapor intrusion impact during each of these sampling events.

Evaluation of Uncertainty: For the evaluation of the uncertainty associated with calculated values (e.g., estimated indoor air concentration due to vapor intrusion), the standard deviations for measured values were combined using the standard statistical rules for combining uncertainty.

- Adding and Subtracting: When adding or subtracting means of measurements, the associated standard deviations are summed as follows:

$$\sigma_x = \sqrt{\sigma_y^2 + \sigma_z^2}$$

- Multiplying or Dividing: When multiplying or dividing means of measurements, the standard deviations are combined as follows:

$$\sigma_x = x\sqrt{\frac{\sigma_y^2}{y^2} + \frac{\sigma_z^2}{z^2}}$$

The uncertainty in difference between measured indoor and ambient VOC concentrations was moderate, with the standard deviation consistently less than the calculated difference. However, the uncertainty in the estimated VOC concentrations due to vapor intrusion was higher with the standard deviations approximately equal to the calculated concentrations. Because of the uncertainty associated with these calculations, the two cases where the difference between the indoor and ambient VOC concentration and the VOC concentration attributable to vapor intrusion were highest are suggestive of an indoor VOC source, but the findings are not definitive.

Finding: *An evaluation of the estimated indoor PCE and TCE concentrations attributable to vapor intrusion indicates an absence of vapor intrusion impacts during the sampling events.*

Evaluation of VOC to Radon Ratios

An evaluation of VOC to radon ratios can also be used to evaluate the likely sources of VOC detected in indoor air. Since radon in subsurface gas, indoor air, and ambient air originates from the subsurface, the radon concentration in each medium is a measure of the mixing of subsurface gas with that medium. If a VOC in indoor air or ambient air originates primarily from the subsurface, then the VOC to radon ratio in that medium should be similar to the ratio in subsurface gas. In contrast, if indoor or ambient sources are contributing to the measured VOC concentration, then the VOC to radon ratio in

these media should be higher than the ratio in subsurface gas. VOC to radon ratios are provided in Table 4.4.1.6.

Table 4.4.1.6: Average VOC to Radon Ratios.

	Environmental Medium		
Test Period	**Sub-Slab**	**Indoor Air**	**Ambient Air**
Average TCE/Radon: Building 418, Altus AFB			
Mar-05	0.024	-	-
Jul-06	0.087	27	95
Dec-06	0.030	0.16	0.21
Average PCE/Radon Building 418, Altus AFB			
Mar-05	0.069	-	-
Jul-06	0.70	0.74	0.92
Dec-06	0.50	0.51	0.57
Average TCE/Radon Residence #1, Hill AFB			
Aug-05	0.045	0.18	-
Mar-06	0.12	0.12	0.97
Mar-06 DP	0.26	0.24	5.5
Average TCE/Radon Residence #2, Hill AFB			
Aug-05	0.037	0.16	-
Mar-06	<0.0022	0.18	0.58

Note: No PCE or TCE detected in indoor or ambient air in March 2005. Radon not measured in ambient air in March 2005 and August 2005. DP = building depressurization sample event.

At Altus AFB, Building 418, the PCE/radon ratios are very similar in all three media for the two sample events where ratios could be calculated in all media. Since the concentration of PCE in subsurface gas samples is much higher than in indoor or ambient air (see Table 4.4.1.4), this indicates that subsurface is the primary source of PCE for both indoor and ambient air for these sampling events. In contrast, the TCE/radon ratio is 5 times to 1000 times higher in indoor and ambient air than in sub-slab gas. In addition, the ratio is similar in indoor and ambient air. This indicates that an ambient source is the primary source of TCE in ambient and indoor air for these sampling events. For Hill AFB, the TCE/radon ratio is similar in sub-slab gas and indoor air for the March 2006 sample event for Residence #1 under both baseline and depressurization conditions indicating that the subsurface was the primary source of indoor TCE for this sampling event. For all other Hill AFB sample events, the TCE/radon ratio in indoor air was at least 4 times higher than the ratio in soil gas indicating a significant contribution of TCE from indoor or ambient sources. For all of the sample events with similar VOC/radon ratios in sub-slab gas and indoor air (i.e., PCE in Building 418 in July 2006 and December 2006 and TCE at Hill AFB Residence #1 in March 2006), the estimated indoor VOC concentration due to vapor intrusion was >50% of the measured indoor VOC concentration (see Tables 4.4.1.4 and 4.4.1.5) also indicating that the subsurface was the primary source of indoor VOC during these sampling events. In contrast, for the other

sample events where the VOC/radon concentration was higher in indoor air than sub-slab gas, the estimated indoor VOC concentration due to vapor intrusion was never more than 25% of the measured indoor VOC concentration. Thus, the VOC/radon ratio appears to be a reliable indicator of the primary source of VOC in indoor air for this dataset. However, the VOC/radon ratio does not indicate whether the magnitude of VI exceeds a regulatory threshold requiring a response action.

Hill AFB Residence #1 Building Depressurization Study

As part of the March 2005 sampling event, a depressurization study was conducted at Residence #1 in order to evaluate VI under "worst case" building conditions under which negative building pressure induces advective flow of soil gas into the building. The depressurization study was conducted following completion of the baseline sampling in Residence #1. During the depressurization study, a box fan placed in a window was used to maintain an average building pressure of -6.0 Pa relative to ambient pressure.

The induction of a negative building pressure resulted in an increase in VI of chemicals present in the subsurface. A clear difference was observed between chemicals with subsurface sources and chemicals associated with background sources (see Figure 4.4.1.1). Compared to the baseline concentration, the indoor TCE concentration doubled under depressurization conditions while the indoor concentration of VOC not associated with subsurface sources decreased by approximately 50%. Although the indoor concentration of radon was similar under baseline and depressurization conditions, the sub-slab concentration decreased indicating a potential depletion of radon from the sub-slab. The attenuation factors for TCE and radon showed similar increases under depressurization conditions (see Figure 4.4.1.2) indicating a similar increase in VI for these two chemicals. Under both baseline and depressurization conditions, the TCE concentration in indoor air was less than 10% of the Hill AFB action level (2.3 ug/m^3).

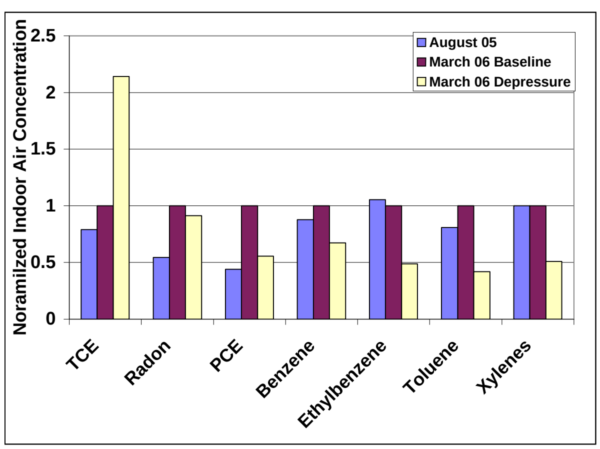


Figure 4.4.1.1: Depressurization Results: VOCS

Note: Indoor air concentration for each VOC normalized by March 2006 baseline concentrations.

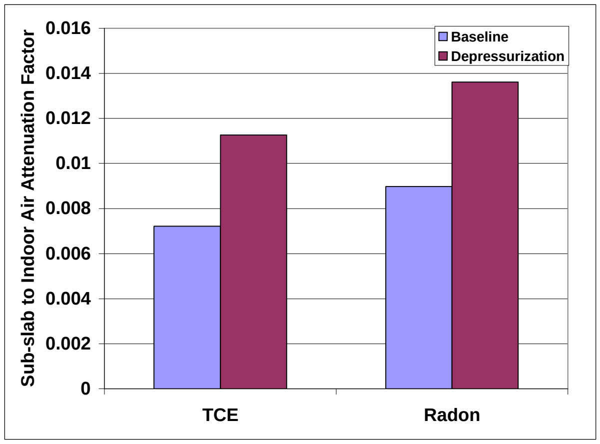


Figure 4.4.1.2: Depressurization Results: TCE and Radon Attenuation Factors

The results of the depressurization study suggest that building pressurization is a useful tool for the evaluation of VI impacts. The relative change in indoor air VOC concentrations under depressurization conditions can be used to distinguish between VOC attributable to subsurface sources and VOC attributable to background sources. In addition, induction of negative building pressure can be used to evaluate the full range of indoor air VOC concentrations likely to occur under normal building operating conditions. This allows the evaluation of "worst case" VI conditions during a single field event.

<u>Finding:</u> *Because the indoor air concentrations of TCE were less than 10% of the Hill AFB action level under building depressurization conditions, it is unlikely that a vapor intrusion impact would occur at Residence #1 under any normal building conditions.*

Overall Evaluation of Vapor Intrusion Impact

For this demonstration, a weight-of-evidence approach has been used to determine the presence or absence of a VI impact during each sampling event. The primary analyses considered are summarized in Table 4.4.1.7. The weight given to each set of analyses and evaluation methods varied between buildings and events. For example, an absence of TCE in sub-slab samples in Residence #2 during the March 2006 sampling event was considered strong evidence of an absence of TCE vapor intrusion, even though the indoor TCE concentration was more than twice the ambient TCE concentration. In contrast, TCE concentrations well above EPA screening levels were detected in indoor air and ambient air during the July 2006 Building 418 sampling event at Altus AFB. During this event, the analysis of radon data was used as the primary tool to determine whether VI was contributing TCE to indoor air. Building depressurization was evaluated during only one sample event (Hill AFB Residence #1 in March 2006). During this event, the depressurization results showed a strong contrast between the subsurface associated VOC

(i.e., TCE) which increased in concentration in indoor air under building depressurization and other VOC (i.e., PCE and BTEX) which decreased in concentration in indoor air under depressurization. During this sample event, building depressurization provided strong supporting evidence that VI was the primary source of TCE in indoor air. However, the concentration of TCE in indoor air under both baseline and depressurization conditions was well below the Hill AFB action level indicating that VI was not causing an unacceptable impact on indoor air quality.

Table 4.4.1.7: Analyses Used to Evaluate Vapor Intrusion Impacts.

Field/Laboratory Analyses	Data Evaluation Methods
VOC concentration in sub-slab gas, indoor air, and ambient air samples	• Presence or absence of VOC in sub-slab samples. • Concentration of VOC in indoor samples compared to regulatory screening values, ambient concentrations, and typical indoor background.
Radon concentration in sub-slab gas, indoor air, and ambient air samples	• VOC/radon ratios in sub-slab gas, indoor air, and ambient air • Estimated VOC concentration in indoor air due to vapor intrusion (calculated based on measured radon attenuation factor).
Impact of building depressurization on VOC and radon concentrations	• VOC concentration in indoor air under baseline and depressurization conditions. • VOC attenuation factor under baseline and depressurization conditions.

As shown by the analysis discussed in this section, the measurement of indoor, ambient, and sub-slab VOC and radon concentrations provides a sufficient data set for a high confidence determination of VI conditions at the time of the sampling event. In addition, building depressurization appears to be a promising tool for the evaluation of VI under "worst case" conditions. Based on the results obtained, radon appears to be a more sensitive tracer than VOC for the movement of soil gas across the building foundation. As a result, the addition of radon to the analytical program for vapor intrusion investigations provides a cost effective ($100/sample) improvement in the understanding of VI conditions.

4.4.2 Movement of VOC Across Key Interfaces

The use of mass flux to evaluate the movement of COC across key interfaces along the VI pathway is a secondary performance criterion. By evaluating the changes in mass flux for each COC along the VI pathway, the impact of each interface on the migration of these COC can be better understood. Mass flux calculations are illustrated in Appendix E and the results are shown in Tables 4.4.2.1 and 4.4.2.2 and are discussed below.

Table 4.4.2.1: Mass Flux Along the Vapor Intrusion Pathway: Altus Demonstration Site.

Environmental Medium or Interface	Mass Flux (ug/day)					
	TCE			PCE		
	March 05	July 06	Dec 06	March 05	July 06	Dec 06
F_{GW1}: Groundwater, under residence (upper 2 ft)	14,700	6,300	2,100	9,600	3,700	960
$F_{GW\text{-}SG}$: Groundwater to deep soil gas	N/C	540	760	N/C	16	59
F_{SG}: Deep soil gas to sub-slab	18-467	NM	242	118-265	NM	NM
$F_{SS\text{-}IA}$: Through building foundation	397*	57	62	1,160*	457	1010

N/C = Not calculated due to the absence of vertical concentration gradient data in groundwater.
NM = Mass flux through soil column not meaningful because measured sub-slab concentration higher than measured soil gas concentration indicating negative concentration gradient in the soil column.
* = Not corrected for ambient air. See Appendix E for calculation details.

Table 4.4.2.2: Mass Flux Along the Vapor Intrusion Pathway: Hill Demonstration Site.

Environmental Medium or Interface	Mass Flux (ug/day)			
	TCE, Residence #1		TCE, Residence #2	
	August 2005	March 2006	August 2005	March 2006
F_{GW1}: Groundwater, under residence (upper 2 ft)	3200	1200	820	490
$F_{GW\text{-}SG}$: Groundwater to deep soil gas	1.1	6.8	14	4.5
F_{SG}: Deep soil gas to sub-slab	2.0	4.0	19	0.16
$F_{SS\text{-}IA}$: Through building foundation	60	Baseline: 0-233 Depressurization: 720 - 1800	53	<8.0 - 380

The range of mass flux through the building foundation is based on mass flux calculated based on estimated TCE concentration in indoor air attributable to vapor intrusion using measured radon attenuation and measured indoor TCE concentration minus measured ambient TCE concentration. See Appendix E for calculation details.

Results of Mass Flux Calculations

As shown in the tables, the calculated mass flux within the top two feet of the water column was consistently greater than the mass flux in the soil column under the demonstration buildings or mass flux through the building foundation. These results suggest that the evaluation of mass flux through shallow groundwater may be a useful tool for a conservative screening of VI. For example, if the mass flux of a VOC through shallow groundwater

below a building is less than the mass flux of that VOC through the building slab required to create a sustained vapor intrusion impact above the applicable regulatory indoor air concentration, then it may be appropriate to consider the groundwater to indoor air VI pathway incomplete.

In contrast to the estimated mass flux though shallow groundwater, the estimated mass flux from groundwater to soil gas and the estimated mass flux through the soil column were typically less than the estimated mass flux through the building. This suggests that our evaluation procedures consistently underestimate the vertical mass flux through the subsurface. Vertical mass flux through the subsurface may occur primarily through secondary features that were not characterized by this study.

Uncertainty in Mass Flux Calculations

Due to the large number of inputs and calculation steps involved in the mass flux calculations, we have not attempted to quantify the uncertainty associated with these calculations. However, based on the quantified uncertainty associated with the VOC concentration values and the likely uncertainty associated with other inputs such as hydraulic conductivity, the mass flux values should be considered order-of-magnitude estimates.

As a result of the large uncertainty associated with the mass flux estimates, these estimates may have limited values for evaluation of VI. However, mass flux in groundwater may still be a useful screening tool. If the mass flux of a VOC in shallow groundwater is less than the mass flux required to create a VI impact in the overlying building, then the VI pathway can probably be considered incomplete. For the purpose of screening, the uncertainty in the estimated VOC mass flux in shallow groundwater can be balanced by the conservative assumption that 100% of this VOC mass could migrate from groundwater to indoor air. Consideration of groundwater mass flux in evaluation of the vapor intrusion pathway has the advantage of incorporating groundwater flow velocity in addition to VOC concentration in the evaluation.

Finding: *Mass flux evaluations may have limited utility for evaluation of the vapor intrusion pathway due to the uncertainty associated with the calculated mass flux values. However, VOC mass flux through shallow groundwater may be a useful tool for pathway screening if groundwater mass flux is less than the mass flux required to create a sustained vapor intrusion impact.*

4.4.3 Spatial and Temporal Variability in VOC Concentrations

The characterization of spatial and temporal variability in VOC concentration is a secondary performance criterion for the demonstration.

Analytical and Sampling Variability

Analytical variability was characterized through the evaluation of laboratory duplicates and surrogate recoveries. For all analyses, analytical variability was very low. For 18

duplicate analyses for PCE and TCE by TO-15, the RPD ranged from 0% to 8%, with an average of 2.5% (see Appendix F). Surrogate recoveries for TO-15 analyses ranged from 84% to 110% with most recoveries between 98% and 102%.

For field duplicate samples, the data quality objective (RPD<30%) was achieved for 78% of field duplicate VOC measurements. Out of 51 field duplicate paired analyses where a VOC was detected in at least one sample, 40 (78%) showed an RPD of <30%, 7 (14%) showed an RPD of 30 to 100% and 4 (8%) showed an RPD of >100%. Well headspace and soil gas samples showed the highest levels of field duplicate variability (See Table 4.4.3.1 and Appendix F).

Field duplicate variability is a combined measure of analytical variability, sample collection variability, and very small scale spatial and temporal variability (i.e., variability on the scale of inches and minutes). For Summa canister samples, field duplicate samples could also be impacted by carry-over contamination due to reuse of the canisters, however, individually certified clean canisters were used for this demonstration. The field duplicate variability was higher than the laboratory variability, indicating that sample collection variability and small-scale field variability were important relative to analytical variability. The evaluation of field duplicates does not allow for the separation of sample collection variability from small-scale field variability.

Table 4.4.3.1: Evaluation of Variability in Field Duplicate Samples.

Environmental Medium	Number of Duplicate Analyses			
	Total	RPD < 30%	RPD 30-100%	RPD > 100%
Groundwater	17	17	0	0
Well Headspace	3	2	1	0
Soil Gas	11	6	2	3
Sub-slab	7	6	1	0
Indoor	10	8	2	0
Ambient	3	1	1	1

Note: A duplicate analysis is one COC measured in a field duplicate at one sample location during a field event and detected in at least one of the two samples. Analysis includes PCE, TCE, and cis-1,2-DCE in groundwater and well headspace samples and PCE and TCE in soil gas, sub-slab, indoor, and ambient samples.

Spatial Variability

Spatial variability was characterized through the collection of samples from three sampling clusters located around the demonstration building, upgradient, midgradient, and downgradient relative to groundwater flow direction (Appendix G, Figures G.3, G.4, and G.5). The collection of three spatially separated samples from each environmental medium allowed us to characterize the spatial variability within each medium during each sampling event. Spatial variability has been evaluated by the coefficient of variation

(CV) for each case in which the target VOC was detected in at least two of the three samples collected. The CV (i.e., standard deviation divided by sample mean) is a normalized measure of variability that is independent of the measurement scale and therefore can be compared between sample sets. In order to characterize lateral (rather than vertical) variability in subsurface samples, spatial variability for soil gas and groundwater sampling points was characterized using the results from the deepest point sampled at each cluster. Spatial variability for well headspace samples was characterized using the shallowest sample from each cluster. The results of the analysis of spatial variability are summarized in Table 4.4.3.1. Results for each sample event are presented in Appendix F, Table F.1.

Table 4.4.3.2: Spatial Variability in VOC Concentration

Sample Medium	Number of Data Sets (1)	Average Coeff. of Variation (CV)	Number of Samples to Estimate Mean +/- 50% (2)	Number of Samples to Estimate Mean +/- 67% (2)
Ambient Air	6	0.55	3	2
Indoor Air	8	0.26	1	1
Sub-slab	12	0.96	10	6
Soil Gas	7	0.96	10	6
Well Headspace	13	0.92	9	5
Groundwater	10	0.90	9	5
GW (Altus)	6	1.35	20	11
GW (Hill)	4	0.21	1	1

Note: 1) Each data set consists of three chemical concentration measurements (TCE or PCE) with at least two detects from one environmental medium collected during a single sampling event. Number of data sets is different for each medium due to differences in frequency of VOC detection. Analyses of individual data sets presented in Appendix F.
2) Based on the observed coefficient of variation in the environmental medium, this is the number of samples required to achieve a sample mean that is equal to the population mean +/- 50% or +/- 67% for 90% of the sample events. Number of samples required (n) = $[(1.64*CV)/Error]^2$.

As shown in Table 4.4.3.2, the spatial variability in subsurface samples was higher than the spatial variability in above ground samples, a result expected based on greater expected mixing of air above ground. Spatial variability was similar for all three types of subsurface gas samples (i.e., sub-slab, soil gas, and well headspace) indicating that all three types of samples provide a similar quality of information about the VOC concentration in soil gas. Specifically, the similarity in variability between deep soil gas points and well headspace samples suggests that the collection of headspace samples from existing shallow groundwater wells may be a useful alternative to installation of new deep soil gas points for the characterization of VOC concentrations in deep soil gas. For groundwater, a large difference in spatial variability was observed between the Hill AFB demonstrations sites and the Altus AFB demonstration site. This difference is likely explained by the observation of a confining layer above the water-bearing unit at Altus AFB. Most of the groundwater monitoring wells at the Altus site were installed within

this confining layer to characterize VOC concentrations between the water-bearing unit and the deep soil gas. VOC concentrations within this confining layer were more variable than at the top of the unconfined water-bearing unit at Hill AFB. For the other environmental media evaluated, spatial variability was similar at the Altus and Hill demonstration sites.

Understanding the spatial variability in VOC concentration within each environmental medium is important for planning an effective site characterization program. When spatial variability is higher, a larger number of samples are required to accurately characterize the medium. If spatial variability is known or can be estimated, we can calculate the number of samples required to estimate the mean VOC concentration with a specified level of accuracy. For example, assuming a normal distribution, the number of samples required to achieve a specified level of accuracy in the estimate of the mean can be calculated as follows:

$$n = [(z \times CV)/E]^2$$

Where

n = The number of samples required
z = The z statistic (1.96 for 95% confidence, 1.64 for 90% confidence, or 1.15 for 75% confidence)
CV = The population coefficient of variation
E = The fractions error in the estimate of the mean (i.e. 0.5 to estimate the mean within +/- 50%)

In other words, if the population variance for a medium is 0.55, then the average of three samples collected from that medium would be within 50% of the population mean approximately 90% of the time ($n = [(1.64 \times 0.55)/0.5]^2 = 3.25$). As shown in Table 4.4.3.1, many more samples are required to accurately characterize the VOC concentration in soil gas than indoor or ambient air. Based on our result, a single indoor air sample will be within 67% of the population mean over 90% of the time. However, six soil gas samples are required to achieve theb same level of accuracy in estimating the mean concentration.

Finding: *High spatial variability in an environmental medium indicates that a larger number of samples are required to accurately define VOC concentrations in this medium. Due to the high level of spatial variability in soil gas VOC concentration, a larger number of soil gas samples are required to accurately characterize the VOC concentration compared to indoor or ambient air.*

Temporal Variability

Short-Term Variability: Temporal variability in VOC concentration on the time scale of days was evaluated at the Altus AFB demonstration site by collecting two samples from each sample point two days apart. An evaluation of short-term temporal variability in indoor and ambient air samples was not possible due to the prevalence of non-detect results in these media during the evaluation of short-term temporal variability. For subsurface samples, low temporal variability was observed in COC concentrations between the two sample events. Out of 31 paired analyses where a VOC was detected in at least one sample, 20 (65%) showed a RPD of <30% (i.e., <1.35x difference), indicating that these analyses would satisfy the typical data quality objective for duplicate samples. Nine paired analyses (29%) showed an RPD of 30 to 100% (i.e., 1.35 to 3 times difference) while only 2 (6%) showed an RPD of >100% (see Table 4.4.3.3 and Appendix F).

Table 4.4.3.3: Evaluation of Short-Term (days) Temporal Variability.

Environmental Medium	Number of Paired Analyses: Event 1 and Event 2			
	Total	RPD < 30%	RPD 30-100%	RPD > 100%
Groundwater	7	6	1	0
Well Headspace	6	1	3	2
Soil Gas	11	7	4	0
Sub-slab	6	6	0	0
Indoor	1	0	1	0
Ambient	0	N/A	N/A	N/A

Note: A paired analysis is one COC measured at one sample location during both sample events and detected during at least one event. Analysis includes PCE, TCE, and cis-1,2-DCE in groundwater and well headspace samples and PCE and TCE in soil gas, sub-slab, indoor, and ambient samples.

The short-term temporal variability was only somewhat higher than that observed for field duplicate samples (see Table 4.4.3.1) indicating that the variability on the time scale of days was largely influenced by sample collection and/or very small-scale field variability. These results provide an indication that short-term temporal variability in COC concentration is not a major source of uncertainty in the evaluation of the vapor intrusion pathway. The finding of low short-term temporal variability is consistent with the findings reported for the Endicott, New York site (Wertz 2006) and others.

Finding: *Based on the results of the demonstration, short-term temporal variability is not a major source of uncertainty in vapor intrusion evaluation. As a result, little additional information about site conditions is provided by the analysis of multiple samples from asample location on the time scale of days.*

Longer-Term Temporal Variability, Hill AFB: At the Hill AFB demonstration site, temporal variability on the time scale of months was characterized by comparing paired samples from August 2005 and March 2006 from each sample location (See Appendix

F). Longer-term temporal variability at Hill AFB was greater than short-term temporal variability at Altus AFB. Out of 39 paired analyses where a VOC was detected in at least one sample, 14 (36%) showed a RPD of <30% (i.e., <1.35x difference), indicating that these analyses would satisfy the typical data quality objective for duplicate samples. 17 paired analyses (44%) showed an RPD of 30 to 100% (i.e., 1.35 to 3 times difference) while 8 (20%) showed an RPD of >100%. The statistical analysis of longer-term temporal variability at Hill AFB is provided as Table F.3 in Appendix F and is summarized in Table 4.4.3.4.

Table 4.4.3.4: Evaluation of Longer-Term (months) Temporal Variability, Hill AFB.

Environmental Medium	Number of Paired Analyses: Event 1 and Event 2			
	Total	RPD < 30%	RPD 30-100%	RPD > 100%
Groundwater	16	8	7	1
Well Headspace	6	3	3	0
Soil Gas	5	0	3	2
Sub-slab	3	0	0	3
Indoor	6	2	3	1
Ambient	3	1	1	1

Note: A paired analysis is one COC measured at one sample location during both sample events and detected during at least one event. Non-detect samples with elevated detection limits not included in analysis

Although the temporal variability in subsurface gas samples (i.e., sub-slab, soil gas, and well headspace) appears to be somewhat higher than in above-ground air samples (i.e., indoor and ambient) or groundwater samples, at least 50% of paired samples from all media had an RPD of greater than 30%, indicating significant variability between samples.

Longer-Term Temporal Variability, Altus AFB: At the Altus AFB demonstration site, the completion of three sampling events allowed for a more comprehensive statistical analysis of longer-term temporal variability. For Altus AFB, longer-term temporal variability has been evaluated by the CV for each case in which the target VOC was detected in at least two of the three temporally-separated samples collected from each sample point. The results of the analysis are summarized in Table 4.4.3.5. Results for each sample point are presented in Appendix F, Table F.2. Temporal variability at indoor and ambient sample points could not be evaluated due to non-detect results for the first sample event with detection limits that were high compared to subsequent sample events.

Table 4.4.3.5: Evaluation of Longer-Term (months) Temporal Variability, Altus AFB.

Sample Medium	Number of Data Sets (1)	Average Coefficient of Variation (CV)	Number of Samples to Estimate Mean +/- 50% (2)	Number of Samples to Estimate Mean +/- 67% (2)
Ambient Air	0	N/A	N/A	N/A
Indoor Air	0	N/A	N/A	N/A
Sub-slab	6	1.02	11	6
Soil Gas	10	0.80	7	4
Well Headspace	5	0.96	10	6
Groundwater	6	0.52	3	2

Note: 1) Each data set consists of three chemical concentration measurements (TCE or PCE) with at least two detects from each sample point sampled during each of three sampling events. Number of data sets is different for each medium due to differences in frequency of VOC detection. Data sets with elevated detection limits for non-detect results were not included. Analyses of individual data sets presented in Appendix F.

2) Based on the observed coefficient of variation in the environmental medium, this is the number of samples required to achieve a sample mean that is equal to the population mean +/- 50% or +/- 67% for 90% of the sample events. Number of samples required (n) = $[(1.64*CV)/Error]^2$.

The analysis of longer-term temporal variability at the Altus AFB site indicates that for subsurface gas samples, temporal variability on the time scale of months is similar to spatial variability. This indicates that the collection of additional spatially-separated subsurface gas samples during a single sampling event or the collection of additional temporally-separated samples from the same sample point provide approximately the same increase in understanding of the VOC concentration in subsurface gas. Based on this understanding, an investigation program of VOC in subsurface gas should be balanced between spatially and temporally separated samples. For example, a plan to collect nine subsurface gas samples might be implemented by installing three spatially separated sample points and conducting three sampling events temporally spaced over one year.

For groundwater, longer-term temporal variability was much lower than spatial variability (CV = 0.52 versus 1.35). Based on the observed variability, only 3 temporally-separated samples would be required to estimate the mean VOC concentration at that point within 50% but 20 spatially-separated samples would be required to achieve the same level of accuracy in the mean VOC concentration for the medium. This indicates that when collecting groundwater samples from within a confining layer above the groundwater-bearing unit, spatially-separated samples provide more information about the chemical distribution than temporally-separated samples.

Finding: *Temporal variability on the time scale of months is higher than temporal variability on the time scale of days and is similar to spatial variability. Based on the similarity between spatial variability and longer-term temporal variability, an efficient investigation program should balance sample collection between spatially-separated sampling points and temporally-separated sampling events.*

4.4.4 Attenuation Factors

Evaluation of attenuation factors is a secondary performance criterion for the demonstration study. As discussed in Section 4.3.2, sub-slab and indoor radon measurements have been used to determine the sub-slab to indoor attenuation factor. As shown in Appendix E, attenuation factors for other environmental media have been determined using the VOC concentrations measured in those media and estimated in indoor air. Deep soil gas to indoor air attenuation factors were calculated using the shallowest well headspace sample at each location rather than the deepest soil gas measurement. The calculated attenuation factors are summarized in Tables 4.4.4.1 and 4.4.4.2, below. For each attenuation factor, the uncertainty associated with the value has been calculated using the standard rules for combining uncertainties for the underlying calculation inputs (see Section 4.4.1).

Table 4.4.4.1: Subsurface to Indoor Air Attenuation Factors for Altus Site Demonstration Building.

Sample Event	TCE	PCE	EPA Default AF
Deep Soil Gas Attenuation Factors (based on well headspace data)			
March 2005	1.4×10^{-4} +/- 1.9×10^{-4}	2.0×10^{-3} +/- 2.4×10^{-3}	0.01
July 2006	5.0×10^{-4} +/- 8.1×10^{-4}	1.0×10^{-3} +/- 1.3×10^{-3}	0.01
December 2006	3.0×10^{-3} +/- 4.2×10^{-3}	4.9×10^{-3} +/- 5.5×10^{-3}	0.01
Groundwater Attenuation Factors (based on shallowest groundwater samples)			
March 2005	1.6×10^{-5} +/- 2.2×10^{-5}	$>1.6 \times 10^{-4}$ +/- 7.0×10^{-5} (2)	0.001
July 2006	2.9×10^{-6} +/- 5.7×10^{-6}	1.7×10^{-4} +/- 3.0×10^{-4}	0.001
December 2006	3.1×10^{-6} +/- 5.8×10^{-6}	3.6×10^{-4} +/- 5.1×10^{-4}	0.001

Note: 1) Attenuation factors based on indoor air concentrations of TCE and PCE attributable to vapor intrusion estimated as described in Section 4.4.1.
2) Lower-bound attenuation factor based on detection limit for non-detect PCE concentration in shallow groundwater.

Table 4.4.4.2: Subsurface to Indoor Air Attenuation Factors for Hill Site Demonstration Buildings.

Sample Event	TCE (Residence #1)	TCE (Residence #2)	EPA Default AF
Deep Soil Gas Attenuation Factors (based on well headspace data)			
August 2005	3.3×10^{-4} +/- 4.4×10^{-4}	1.6×10^{-4} +/- 2.5×10^{-4}	0.01
March 2006	2.1×10^{-4} +/- 2.9×10^{-4}	$<7.7 \times 10^{-6}$ +/- 1.3×10^{-5}	0.01
Groundwater Attenuation Factors (based on shallowest groundwater samples)			
August 2005	1.0×10^{-5} +/- 1.4×10^{-5}	1.9×10^{-5} +/- 2.4×10^{-5}	0.001
March 2006	1.2×10^{-4} +/- 1.8×10^{-4}	$<2.0 \times 10^{-6}$ +/- 2.5×10^{-6}	0.001

Note: Attenuation factors based on indoor air concentrations of TCE and PCE attributable to vapor intrusion estimated as described in Section 4.4.1.

At both the Altus and Hill demonstration sites, the calculated deep soil gas and groundwater to indoor air attenuation factors were consistently less than the USEPA

default values. However, significant variability in the attenuation factors was observed for each site. At the Altus site, the deep soil gas and groundwater attenuation factors for TCE were approximately 10 times to 100 times lower than the PCE attenuation factors, indicating significantly greater attenuation of TCE than PCE. The lower attenuation factors for TCE reflect higher TCE concentrations in the subsurface and lower TCE concentration in indoor air relative to PCE. This disparity suggests either greater attenuation of TCE within the soil column or an unidentified shallow source of PCE near the demonstration building. At Hill AFB, the TCE concentration in shallow groundwater was similar at Residence #1 and Residence #2 (e.g., 1.6 ug/L and 1.8 ug/L for the March 2006 sampling event). However, for the March 2006 sampling event, there was a significant difference in TCE concentration below the building foundations, resulting in a 100 times difference in groundwater to indoor air attenuation factors between the two residences.

Evaluation of Uncertainty: The uncertainty in the calculated subsurface-to-indoor air attenuation factors was large, with the standard deviation consistently larger than the calculated attenuation factor. The key sources of uncertainty in these calculations are i) high spatial variability in subsurface VOC concentration, and ii) uncertainty associated with the estimated indoor VOC concentration attributable to vapor intrusion (see Section 4.4.1).

Although our evaluation shows high uncertainty in the calculated attenuation factors, each of these attenuation factors was based on a minimum of three subsurface, three indoor air, and one ambient air measurement. As a result, these attenuation factors are certainly much more accurate that those typically calculated from large databases, such as the EPA vapor intrusion database. Such attenuation factors are typically calculated from a single subsurface measurement and a single indoor air measurement with no correction for ambient or indoor sources. As a result, attenuation factors from databases likely have uncertainties of greater than one order of magnitude.

Finding: *Attenuation factors calculated for the demonstration site were consistently lower than the EPA default values. However, large variability was observed between attenuation factors at each demonstration site and high uncertainty was observed in the calculated attenuation factor values.*

4.4.5 Site Physical Characteristics

The demonstration program consisted of detailed evaluations of vapor intrusion at a total of three buildings at two demonstration sites. This provided only a limited dataset to identify relationships between site physical characteristics and vapor intrusion. At each demonstration site, the soil permeability was characterized through the measurement of intrinsic permeability, native hydraulic conductivity, and air and water filled porosity, on soil cores collected during the installation of subsurface sampling points.

At the Hill AFB site, geotechnical testing indicated that both soil permeability and air filled porosity were lower at Residence #1 than Residence # 2, see Table 4.4.5.1. Based on these observations, one would predict less potential for VI at Residence #1 compared to Residence #2. However, the attenuation factor analysis indicated similar VOC attenuation at the residences during the first sampling event and less VOC attenuation at Residence #1 compared to Residence #2 during the second sampling event. In fact, during the second sampling event, no VOC were detected below the foundation of Residence #2, indicating significantly less migration of VOC from groundwater compared to Residence #1.

At the Altus AFB demonstration site, soil permeability appeared to be somewhat lower than Hill AFB Residence #1, however, no clear differences were observed in VOC attenuation between the Hill and Altus demonstration sites (see Section 4.3.4). The full results of the geotechnical testing are presented in Appendix G.

Table 4.4.5.1: Results of Geophysical Testing.

Sample Location	Intrinsic Permeability to Water (cm^2)	Native Hydraulic Conductivity (cm/sec)	Air Filled Porosity (% of bulk volume)
Hill AFB Residence #1	5.6×10^{-11} +/- 4.0×10^{-11}	5.6×10^{-6} +/- 4.0×10^{-6}	5.3% +/- 3.0%
Hill AFB Residence #2	1.6×10^{-9} +/- 2.4×10^{-9}	1.6×10^{-4} +/- 2.3×10^{-4}	12% +/- 2.4%
Altus AFB Building 418	3.3×10^{-12} +/- 3.4×10^{-12}	3.3×10^{-7} +/- 3.4×10^{-7}	12% +/- 2.3%

Note: Each value is the average of measurements from nine soil cores collected during sample point installation.

Vadose Zone Permeability Testing

In order to better understand the influence of unsaturated soil permeability on the migration of VOC along the VI pathway, soil permeability was measured at a number of the subsurface monitoring points around the test building. The testing procedures are described in Section 3.5 and the data analysis method is shown in Appendix E. Calculated permeabilities are shown in Tables 4.4.5.2 and 4.4.5.3, below.

Table 4.4.5.2: Soil Permeability for Altus Site Demonstration Building.

Sample Point	Soil Permeability (cm^2)	
	July 2006	**December 2006**
Upgradient Cluster		
SG-1	1.1×10^{-7}	NM
SG-4	3.3×10^{-10}	1.2×10^{-10}
MW-4	1.9×10^{-10}	1.6×10^{-10}
Midgradient Cluster		
MW-11	1.6×10^{-8}	9.8×10^{-9}
Downgradient Cluster		
SG-8	3.5×10^{-8}	3.0×10^{-8}
SG-6	NM	5.0×10^{-8}
MW-8	2.8×10^{-8}	1.5×10^{-8}
MW-6	2.4×10^{-10}	2.9×10^{-9}

Note: NM = Not measured during sample event.

Table 4.4.5.3: Soil Permeability for Hill Site Demonstration Buildings.

Sample Point	Soil Permeability (cm^2)	
	Residence #1	**Residence #2**
SG-3 (Upgradient)	NM	6.7×10^{-8}
SG-4 (Upgradient)	6.1×10^{-10}	1.3×10^{-9}
SG-12 (Downgradient)	3.4×10^{-10}	8.5×10^{-11}
MW-1 (Upgradient)	7.1×10^{-11}	5.8×10^{-11}
MW-5 (Midgradient)	5.7×10^{-10}	7.3×10^{-10}
MW-9 (Downgradient)	6.6×10^{-11}	NM

NM = Not measured during sample event.

At Altus AFB, the measured vadose zone permeability is consistent with literature values for silty soil, the predominant soil type observed during the installation of the sample points in March 2005. Lower permeabilities were measured at locations with higher soil moisture (i.e., the upgradient cluster where perched groundwater is observed and the deepest measurement location at the downgradient cluster screened below the potentiometric surface of the water-bearing unit). The high permeability measured at SG-1 (completed 1 ft bgs) may be attributable to preferential flow paths extending to the ground surface.

Finding: *The hypothesis that locations with lower soil permeability and lower air-filled porosity are less susceptible to vapor intrusion was not supported by the limited data set obtained. No clear relationship was observed between soil permeability and VOC attenuation.*

4.5 Recommendations for Vapor Intrusion Sample Collection

Under EPA guidance, groundwater and soil gas concentrations can be compared to published screening values to identify sites at which no further evaluation of VI is required. The results of this demonstration support the following recommendations specific to the collection of groundwater or soil gas samples for the purpose of vapor intrusion pathway screening.

4.5.1 Groundwater Samples

Placement of Sample Points

In order for a groundwater plume to pose a potential VI threat, VOC must be able to diffuse from groundwater to vadose zone soil gas across the top of the water table. Because diffusion through groundwater is very slow, only VOC present near the top of the water table pose a potential VI threat. A variety of factors can contribute to VOC concentrations at the top of the water table that are lower than those found at greater depth (Nichols and Roth 2006). In other cases, VOC concentrations at the top of the water table may be higher than those found at depth. As a result, the top of the water table should be targeted when collecting groundwater samples for vapor intrusion screening. Typically, monitoring wells with 10 ft screens are used for delineation and long-term monitoring of groundwater plumes. However, researchers have found that the majority of traditional monitoring wells with longer screens have vertical flow of water within the well (Elci, Molz et al. 2001), making it difficult or impossible to obtain a depth discrete groundwater sample from such a well. As a result, smaller screened intervals (1 to 2 ft) are more appropriate for the evaluation of vapor intrusion.

Study Findings: At both Altus AFB and Hill AFB, monitoring wells with 1 ft screen intervals placed at the top of the water table exhibited VOC concentrations markedly different than near-by wells with 10 ft screens extending deeper in the groundwater-bearing unit. At Hill AFB, the 1-ft screened monitoring wells at the top of the water table exhibited TCE concentrations approximately 3 to 20 times lower than those measured at near-by wells with 10-ft screens, however, at Altus, the 1ft screened monitoring well at the top of the water-bearing unit exhibited TCE concentrations approximately 2 to 20 times higher than those measured at near-by wells with 10-ft screens placed deeper in the groundwater-bearing unit. At Altus, the shallow groundwater-bearing unit is confined, limiting recharge and potentially creating other factors resulting in high VOC concentrations near the top of the water-bearing unit. However, in both study sites, the difference in VOC concentration between 1-ft screen wells and 10-ft screen wells illustrates the importance of short screen lengths placed at the top of the water-bearing unit for the evaluation of the VI pathway.

Recommendation: Groundwater samples used for screening the VI pathway should be collected from monitoring wells with short screens (≤ 2 ft) placed at the top of the water table. At some sites, a cluster of vertically spaced wells will be required to account for

temporal fluctuation in water table elevation and ensure that samples from the top of the water table can be collected during all sampling events.

Sample Collection Methods

No special groundwater sampling methods are required to obtain samples for evaluation of vapor intrusion.

4.5.2 Soil Gas Samples

Placement of Sample Points

A soil gas sample point is a temporary or permanent location within the vadose zone soils from which a soil gas sample is collected. Although a variety of methods have been used for the installation of soil gas sampling points, a comprehensive comparison of these methods is not available. The choice between temporary or permanent sample points should be made considering the potential need to collect multiple samples over time from the same location.

Samples from soil gas sample points may be used for either pathway screening or direct evaluation of vapor intrusion impacts. When used for pathway screening (i.e., to evaluate whether VOC are migrating from the source into soil gas), the sample points should be placed in close proximity to the source. For groundwater sources, the sample points should be placed in close proximity to the water table (unconfined conditions) or directly above the confining unit (confined conditions). For soil sources, the sample point should be placed at the edge of the soil source area closest to the potentially impacted building. For evaluation of VI impacts (i.e., to evaluate the migration of VOC from soil gas into buildings), the sample points should be placed in close proximity to the potentially impacted building, typically installed through the building foundation.

Study Findings: For the building-specific evaluation of vapor VI impacts, collecting soil gas samples adjacent to the building, rather than below the building foundation, eliminates the difficulty of obtaining access to the inside of the building. However, there is significant uncertainty regarding whether samples collected adjacent to a building are representative of chemical concentrations below the building. At two of the three test buildings evaluated, shallow soil gas VOC concentrations below the building were higher compared to VOC concentrations in soil gas adjacent to the building. At the third building, shallow soil gas VOC concentrations were highest at one of the two sample clusters completed adjacent to the test building. The dataset obtained was not sufficient to determine whether this observed variability between below building and adjacent sample points was higher than or similar to, the overall spatial variability observed in soil gas VOC concentration.

Recommendation: Based on the uncertainty concerning the reliability of samples collected adjacent to a potentially impacted building, below foundation samples should

be used for the collection of soil gas samples used to evaluate building-specific vapor intrusion impacts.

Sample Purge Volume

Prior to sampling a soil gas point, the point and associated sample line must be purged to remove gas within the sample point and line that may not be representative of subsurface VOC concentrations. The purge volume should be sufficient to thoroughly flush the sample point and line but should minimize the disturbance of subsurface gas so that the sample collected is representative of the immediate vicinity of the sample point.

Study Findings: At each of the two demonstration sites, a purge study was conducted to determine the effect of increasing purge volumes on sample VOC concentrations. For the points tested, samples were collected following purges of 1 to 8 line volumes (i.e., the volume of the sample point and associated tubing). The COC concentrations measured in the samples typically increased between purges of 1 and 2 line volumes and were relatively stable between 2 to 8 line volumes. COC concentrations were most stable in the sample points with the lowest total line volumes, but were somewhat more variable for sample points with larger line volumes. These results indicating stable VOC concentrations over a broad range of sample line purge volume are similar to those reported by other investigators at the Raymark Superfund site (DiGiulio, Paul et al. 2006) and Cody, Wyoming site (McAlary and Creamer 2006) and indicate that VI investigation results are unlikely to be distorted by minor variations in soil gas sample collection methods.

Recommendation: A purge volume equal to 3 line volumes should be used to ensure thorough flushing of the sample collection line but minimize the flow of gas in the subsurface around the sample collection point induced by the purging process. Required purge volumes should be minimized by using sample tubing with a small inside diameter such as 1/8th inch Nylaflow^{TM} tubing (line volume = 1mL/ft).

Soil Gas Sample Leak Tracers

Leaks around sample collection points, or in sample lines, can result in samples that are not representative of actual VOC concentrations at the sample point. Unlike soil or water samples, it is difficult to ensure that a gas sample originated from the location of the sample point. Ambient air may enter the sample container through leaks in the sample lines or around the sample point casing. Vacuum testing of the sample lines can be used to demonstrate an absence of line leaks, and leak tracer compounds can be used to evaluate the integrity of both the sample point casing and the sample line.

Study Findings: During the study, a combination of vacuum testing and leak tracer compounds were used to evaluate the integrity of soil gas sample point casings and sample lines. If leak tracer compound was detected in a soil gas sample, the magnitude of the leak was estimated by comparing the concentration of leak tracer in the sample to

the concentration released around the sample point (approximately 5% by volume). When leak tracers are used during sample collection, it is common to find detectable concentrations of leak tracer in the soil gas sample (Personal communication from Matt Lavis of Shell and Todd McAlary of Geosyntec), and therefore, leakage rates of less than 1% were not considered significant. However, during some sample events, the presence of leak tracer compound in the soil gas samples indicated leakage rates between 1% and 10% for some samples. Application of a fresh bentonite seal around the top of the sample point casing prior to sample collection reduced the concentration of leak tracer in the sample, indicating that the leakage was primarily around the sample point casing and not through the sample lines.

During one sample event, the leak tracer itself caused significant problems. During this sample event, 1,1-difluoroethane (1,1-dfa, the propellant in duster spray) was used as the leak tracer. In several samples, 1,1-dfa in the soil gas samples at concentrations indicating a leakage rate of less than 1% resulted in elevated detection limits for the target VOC, resulting in a failure to meet the data quality objective for detection limits in these samples. For subsequent sampling events, sulfur hexafluoride (SF_6), a compound that does not cause interference with the detection of VOC by TO-15, was used as the leak tracer compound.

Recommendation: A combination of vacuum testing of lines and leak tracers should be used to ensure the integrity of soil gas samples. Above-ground sample lines should be vacuum tested for tightness prior to sample collection and a leak tracer compound should be released around the sample point casing during sample collection. Common leak tracer compounds include pentane, isopropyl alcohol, helium, and SF_6. The selection of the leak tracer compound should be coordinated with the analytical laboratory to ensure that its presence in soil gas samples will not interfere with the analysis of target compounds. If leak tracer compound is detected in the soil gas sample, then the leakage rate should be estimated and corrective action implemented as described in Table 4.5.2.1.

Table 4.5.2.1: Evaluation of Leakage in Soil Gas Samples.

Leakage Rate (by volume)	**Corrective Action**
<1%	None. Leakage is not significant
1% to 10%	Reduce leakage for future sampling events. Sample results should be considered valid, but the source of leakage should be identified and controlled during future sampling events.
>10%	Reject results and resample. Analytical results may not be representative of actual COC concentrations in soil gas at the sample point. Resample these points using improved sample collection methods to reduce leakage.

Sample Containers

Summa canisters are the most commonly used containers for the collection of soil gas or air samples for off-site analysis of VOC. These canisters are typically provided by the laboratory and are reused many times. As a result, care must be taken to prevent carry-over contamination between sample events. TO-15 analytical procedures require batch certification of Summa canisters following cleaning (i.e., testing of one canister per 20 to ensure an absence of contamination). Most laboratories will provide individual clean certification (i.e., testing of all canisters following cleaning) for an additional charge of approximately $75 per canister.

Study Findings: During the project, one batch of analytical results was rejected due to problems with carry-over contamination in the Summa canisters despite batch certification. Other researchers have reported similar problems, although the prevalence of carry-over contamination in batch certified Summa canisters is not known and likely varies between laboratories. Individually certified clean Summa canisters and flow controllers were used for subsequent sampling events and no further evidence of carry-over contamination was noted.

Recommendation: Individually certified clean Summa canisters should be requested when Summa canisters are used for VOC analysis of soil gas or air. Recent research indicates that Tedlar bags are a suitable alternative to Summa canisters for VOC when the holding time is less than two weeks (Paul 2007), however, some regulators may not accept results for samples collected in Tedlar bags. For larger field programs, use of an on-site mobile laboratory may be a cost-effective alternative to off-site analysis. When using an on-site laboratory, gas samples may be collected in either Tedlar bags or gas-tight syringes.

4.6 Recommended Approach for Building-Specific Investigation of Vapor Intrusion

Most available regulatory guidance recommends a step-wise approach for the evaluation of potential vapor intrusion sites based on COC screening, pathway screening, and receptor evaluation. Because a single source area has the potential to impact multiple receptors, this step-wise approach will generally be the most efficient and cost-effective for the evaluation of vapor intrusion. Regulatory guidance should be consulted for appropriate COC and pathway screening procedures.

For sites where COC screening and pathway screening indicate COC may be migrating from a local source through soil gas towards a building or buildings, a field investigation is required to determine the presence or absence of vapor intrusion impacts to these specific buildings. In this section, we provide our recommendation for a cost-effective field investigation program that is likely to provide a reliable determination of the presence or absence of a vapor intrusion impact. The investigator should keep in mind that i) applicable regulatory guidance may impose additional or different investigation

requirements and ii) the understanding of vapor intrusion is evolving rapidly and recommended investigation approaches are likely to continue to evolve.

4.6.1 Building-Specific Vapor Intrusion Screening

A building-specific field investigation is typically recommended when VOC concentrations collected in close proximity to the source (i.e., in deep soil gas or shallow groundwater) exceed conservative screening concentrations. However, prior to a detailed evaluation of the target building, the investigator should conduct receptor screening by comparing VOC concentrations in indoor air or below the building foundation to conservative screening concentrations. The decision on whether to conduct screening sampling of indoor air or below foundation soil gas will be building specific and may include the following considerations:

Indoor Sources: Are indoor sources of VOC likely to contribute to measured VOC concentrations in indoor air?

Building Access: Will building occupants allow penetration of the building foundation for the collection of below-foundation gas samples?

Regulatory Requirements: Do applicable regulations or guidance specifically require the use of indoor or below-foundation samples for screening?

For a typical, single-family residential building, one indoor air sample or three below foundation soil gas samples should be collected. A larger number of samples are required for screening due to the higher spatial variability in the distribution of VOC within soil gas. If VOC concentrations are non-detect, or below conservative screening concentrations, then no further immediate evaluation of VI is required for the building. However, additional follow-up monitoring may be warranted at some buildings to evaluate the potential for intermittent VI impacts to occur at other times. If VOC concentrations are above conservative screening concentrations, then additional evaluation of the building should be conducted. Because VOC present below the building foundation may originate from inside the building or from ambient air, caution should be used in the interpretation of sample results indicating the presence of low VOC concentrations below the building foundation (McHugh, DeBlanc et al. 2006).

4.6.2 Building-Specific Vapor Intrusion Evaluation

For buildings with VOC present in, or below, the building at concentrations above conservative screening levels, the following comprehensive sampling program is likely to provide a clear determination of the presence or absence of a VI impact at the target building during the sampling event.

Sample Collection and Analysis Program

In order to understand the origin of any VOC detected in the target building, samples for VOC and radon analysis should be collected simultaneously from below the building foundation, indoors and outdoors. A recommended typical sampling program is summarized in Table 4.6.2.1. The use of consistent investigation methods between building locations will provide comparable results that serve to provide an increased understanding of vapor intrusion processes over time.

Table 4.6.2.1: Recommended Typical Sample Collection Program for Evaluation of Vapor Intrusion.

Environmental Medium	Analyses	Sample Duration	Sample Container	Number of Samples	Sample Locations
Ambient air	VOC by TO-15[1]	24 hr	6 L Summa	1	Upwind
	Radon[2]	Grab	0.5 L Tedlar	1	
Indoor air	VOC by TO-15[1]	24 hr	6L Summa	1 - 2[3]	Lowest floor
	Radon[2]	Grab	0.5 L Tedlar	1 - 2[3]	
Sub-slab gas	VOC by TO-15	Grab	0.4 L or 1L Summa	3 - 5[3]	Distributed below lowest floor
	Radon[2]	Grab	0.5 L Tedlar	3 - 5[3]	

Note: 1) TO-15 SIM may be required for indoor and ambient air samples to achieve detection limits below regulatory screening values. TO-15 analyses are conducted by numerous commercial laboratories. The TO-15 analyte list may vary between laboratories and should be reviewed to ensure inclusion of all volatile COC.
2) Radon samples analyzed by Dr. Doug Hammond (dhammond@usc.edu) at the University of Southern California Department of Earth Sciences using the extraction method of Berelson, 1987 and the analysis method of Mathieu, 1998.
3) Recommended number of samples for a typical residence with a 1000 - 2000 ft^2 foundation. Additional samples may be appropriate for larger structures.

The recommendation to collect more sub-slab gas samples than indoor air samples is based on the finding that spatial variability in VOC concentration is much higher in subsurface gas than in indoor or ambient air. As a result, a larger number of spatially-separated samples are required from below the building foundation in order to characterize the distribution of VOC in this medium. Although 1 or 2 indoor air samples will be sufficient to characterize VOC concentrations in this medium, additional targeted indoor air samples should be added, if needed, to characterize the impact of suspected indoor sources that cannot be removed from the building during the sampling event.

Data Evaluation

The identification of vapor intrusion impacts should be based on a weight-of-evidence approach using the following data evaluation methods:

Indoor Air Data: If indoor VOC concentrations are below indoor screening levels then no further immediate evaluation of vapor intrusion is required. Additional follow-up monitoring may be warranted at some buildings to evaluate the potential for intermittent vapor intrusion impacts to occur at other times.

<u>*Evaluation of Potential VOC Sources:*</u> If indoor VOC concentrations exceed indoor screening levels, then VOC and radon concentrations should be evaluated to help identify the most likely source, or sources, of the indoor air impacts.

- *Evidence of Ambient Sources*: Ambient VOC concentrations greater than or similar to indoor VOC concentrations indicate that ambient sources are likely the primary source of VOC in indoor air.
- *Evidence of Indoor Sources*: Indoor VOC concentrations >10% of below foundation concentration, and/or large differences in below foundation to indoor air attenuation factors between VOC, indicate that indoor sources are likely the primary source of one or more of the VOC in indoor air. For example, a PCE attenuation factor of 0.03, and a TCE attenuation factor of 0.001 would suggest a likely indoor source of PCE.
- *Evidence of Vapor Intrusion*: The following factors together indicate that VI is likely the primary source of observed indoor air impacts: i) indoor VOC concentrations greater than ambient VOC concentrations, ii) below foundation to indoor air attenuation factors <0.01 and, iii) below foundation to indoor air attenuation factors similar for all VOC and for radon.

For buildings where both indoor or ambient sources and vapor intrusion are contributing to the observed indoor air impact, the indoor VOC concentration attributable to VI ($C_{ia\text{-}vi}$) can be estimated as:

$$C_{ia\text{-}vi} = C_{sg} \text{ x } AF_{radon}$$

Where C_{sg} is the VOC concentration in soil gas and AF_{radon} is the measured radon attenuation factor. Where C_{sg} is the VOC concentration in soil gas and AF_{radon} is the measured radon attenuation factor (i.e., ($radon_{indoor}$-$radon_{ambient}$)/$radon_{sub\text{-}slab}$). Using this approach, the contribution of indoor VOC sources can be accounted for and the calculated indoor VOC concentration attributable to vapor intrusion can be compared to regulatory standards for indoor air to determine the need for mitigation of vapor intrusion impacts.

<u>*Impact of Variability on the Evaluation*</u>: Analytical, spatial, and temporal variability in measured VOC concentrations results in some uncertainty regarding the presence or absence of a VI impact. If the average measured VOC concentration during a sample event is close to the applicable screening value (e.g., +/- 50%), then additional sampling may be warranted to provide a more definitive determination of the vapor intrusion condition. When the initial investigation of the vapor intrusion pathway does not yield a definitive determination of the presence or absence of a VI impact, then the cost of further investigation must be balanced against the cost of mitigation. If the initial investigation indicates that a vapor intrusion impact is unlikely, but the finding is not definitive (i.e., the VOC concentration is close to, but below the screening value), then 1 to 3 follow-up sampling events is likely to be sufficient to confirm the initial findings. If

the initial investigation indicates that a vapor intrusion impact is likely, but the finding is not definitive (i.e., the VOC concentration is close to, but above the screening value), then longer-term monitoring may be required and further monitoring is likely to confirm an impact in the many cases. In this case, installation of a mitigation system may be the most cost-effective approach because further monitoring is likely to indicate that mitigation is, in fact, required. It should be noted, however, that the installation of a mitigation system at a site where a VI problem has not been confirmed may create the perception that an actual VI problem existed prior to the installation of the system. This may create concerns regarding exposure prior to installation of the system, or during periods where the system does not operate, and may increase the risk of litigation and third-party claims.

Optional Additional Evaluation Methods

The following additional field evaluations may provide an improved understanding of vapor intrusion conditions in the test building.

Cross-Foundation Pressure Gradient: The pressure gradient across the building foundation largely controls the movement of VOC and other gases between the shallow soil and the building interior. When the building foundation has cracks or penetrations that support gas flow, gas will flow from the shallow soil into the building during times when the building has a lower pressure than the soil (i.e., negative building pressure) and gas will flow from the building into the shallow soil during times when the building has a higher pressure than the soil (i.e., positive building pressure). A variety of building and meteorological conditions can affect the pressure gradient across the building foundation, including: building operating conditions, ambient temperature, wind conditions, changes in barometric pressure, and pressurized gas sources.

Cross-foundation pressure gradient can be measured using a differential pressure transducer with data logger such as the Omniguard 4. These pressure transducers can measure positive and negative pressures gradients, providing an indication of advective forces into and out of the building. The pressure transducer contains two pressure ports, a reference port which is open to the indoor atmosphere and another port which was isolated in the sub-slab atmosphere by tubing extending through the building slab and sealed from the indoor atmosphere.

Cross-foundation pressure gradient measurements can be used determine the driving force for transport across the building foundation during the sample collection event. The predominant driving force for flow across the building foundation can be determined as follows:

- A consistently high building pressure (i.e., positive building pressure) indicates the potential for airflow from the building into the shallow soils.

- A consistently low building pressure (i.e., negative building pressure) indicates the potential for airflow from the shallow soils into the building.

- A pressure gradient varying between positive and negative building pressures indicates the potential for bi-directional flow between the building and shallow soil gas. Sufficient data should be collected to confidently determine whether the average gradient is positive, negative, or zero.

Note that variations in pressure gradient at different locations within the building may result in some transport in the opposite direction from that suggested by the measured pressure gradient. However, the measured gradient will indicate the predominant direction of flow through the foundation.

Induced Building Depressurization: Temporal variations in cross-foundation pressure gradient may result in temporal variations in the presence and magnitude of vapor intrusion impacts. In other words, the magnitude of VI impacts may be highest during periods of sustained negative building pressure. If sampling is conducted only under normal building operating conditions, several sampling events may be required to determine the full range of potential vapor intrusion impacts. However, through the induction of a negative building pressure, building conditions can be created allowing the maximum magnitude of VI impact to be evaluated during a single sampling event. Following the collection of baseline samples, a low-pressure condition can be created in the target building through the placement of a box fan in the window blowing out. Following a stabilization period of 6 to 12 hours, the original sampling program can be repeated. The two datasets generated from this program (baseline and depressurization) can be used to evaluate the potential for VI impacts over a range of building pressurization conditions.

4.6.3 Evaluation Costs

Costs for the recommended building-specific investigation of VI have been estimated using typical laboratory costs and assuming that investigations of multiple buildings will be conducted by an experienced team of investigators. Labor hours will likely be higher for personnel without significant experience in vapor intrusion investigations due to the additional time required for project planning and reporting. Similarly, labor hours will likely be higher for the investigation of a single building because planning and reporting tasks cannot be spread between several buildings. Typical unit costs for laboratory analyses and materials are provided in Table 4.6.3.1, typical costs for initial screening are provided in Table 4.6.3.2, and typical costs for comprehensive building evaluation are provided in Table 4.6.3.3.

Table 4.6.3.1: Typical Unit Costs for Vapor Intrusion Analyses.

Item	Typical Cost
VOC analysis by TO-15 (Includes Summa can rental for individually certified clean canisters)	$310
VOC analysis by TO-15 SIM (Includes Summa can rental for individually certified clean canisters)	$340
Radon analysis (Includes Tedlar bag for sample collection)	$110
Hammer drill for installation of sub-slab sample points (1 day rental)	$50
Differential pressure transducer/logger (purchase)	$1300
Differential pressure transducer/logger (1 week rental)	$350

Table 4.6.3.2: Typical Costs for Screening of a Single Family Residence.

Item		Estimated Cost
Labor:	Project planning - 2 hrs; field program - 4 hrs; analysis and reporting - 4 hrs.	$1,000
Laboratory:	Indoor air - 1 sample for VOC analysis by TO-15 SIM or Sub-slab - 3 samples for VOC analysis by TO-15.	$340 to $930
Materials:	Indoor air - none or Sub-slab - Hammer drill rental	$0 to $50
	Total Costs: Indoor Air Screening	**$1,300**
	Total Costs: Sub-Slab Screening	**$2,000**

Note: Assumed labor costs of $100/hr.

Table 4.6.3.3: Typical Costs for Evaluation of a Single Family Residence.

Item		Estimated Cost
Standard Evaluation		
Labor:	Project planning - 8 hrs; field program - 10 hrs; analysis and reporting - 8 hrs.	$2,600
Laboratory:	Ambient air - 1 sample for VOC analysis by TO-15 SIM and 1 sample for radon analysis. Indoor air - 2 samples for VOC analysis by TO-15 SIM and 2 samples for radon analysis. Sub-slab - 4 samples for VOC analysis by TO-15 and 4 samples for radon analysis.	$3,060
Materials:	Hammer drill rental	$50
	Total Costs for Standard Evaluation	**$6,700**
Optional Additional Evaluations		
Building Depressurization: Following collection of baseline samples, induce negative building pressure and repeat field sampling program (10 hrs labor plus sample laboratory program as baseline sampling)		$4,060
Cross-Foundation Pressure Gradient: Measure cross-foundation pressure gradient during field program (1 hr labor plus transducer rental)		$450

Note: Assumed labor costs of $100/hr.

4.6.4 Impact of Investigation Program on Attenuation Factor Accuracy

As discussed in Section 1.3, at least 24 states have issued or are developing guidance on vapor intrusion. These guidances provide disparate and sometimes conflicting recommendations for the field investigation of vapor intrusion. As a result, there is currently no standard practice for the field investigation of VI and investigation approaches vary widely between sites. However, the results of this demonstration indicate that spatial variability in subsurface VOC concentrations is a significant source of uncertainty and should be accounted for in the design of the VI investigation program. Based on this finding, the investigation program presented in Section 4.6.2 recommends the collection of a greater number of sub-slab gas samples (3-5) than indoor air samples (1-2). The impact of sample design on the accuracy of the vapor intrusion has been evaluated below through an evaluation of the impact of sample design on the accuracy of calculated attenuation factors.

Use of Attenuation Factors in Vapor Intrusion Evaluations: Attenuation factors, the ratio of indoor air to subsurface VOC concentration, have been widely used by the EPA and others to characterize VI at corrective action sites. Upper-bound attenuation factors have, in turn, been used to develop subsurface VOC concentration screening values considered protective against VI impacts (EPA, 2002). For this purpose, the EPA has developed a database of attenuation factors measured at corrective action sites where vapor intrusion has been evaluated. After attempting to correct for the influence of background indoor

air sources, the EPA has identified an upper-bound (90th or 95th percentile) attenuation factor and used this attenuation factor to calculate subsurface VOC concentrations that are not expected to cause unacceptable impacts to indoor air. For example, the 2002 EPA vapor intrusion guidance uses a sub-slab attenuation factor of 0.1. As a result, a sub-slab benzene concentration of less than 31 ug/m^3 would be considered unlikely to cause an indoor air benzene concentration of greater than 3.1 ug/m^3 (i.e., the target indoor air concentration for 10^{-5} risk). The use of a 95th percentile attenuation factor to calculate subsurface screening concentrations is usually interpreted as being conservative (protective) for 95% of buildings. However, if spatial variability in VOC concentration contributes significantly to the variability in the measured attenuation factor, then 95th percentile attenuation factors will be higher than the value needed to protect 95% of buildings.

The attenuation factors in the EPA vapor intrusion database have been calculated using single paired subsurface and indoor air VOC measurements. Because of spatial variability in VOC concentrations in the subsurface, the attenuation factor calculated based on a single subsurface and a single indoor VOC measurement will vary from the true attenuation for that residence. As a result, the 95th percentile attenuation factor from a database of single paired subsurface and indoor air measurements will reflect both i) the error between the measured attenuation factor and the actual attenuation factor for each building due variability on VOC concentration and ii) the actual variability in VOC attenuation between buildings. The added variability associated with the error between the measured attenuation factor and the true attenuation factor for each building results in a 95th percentile attenuation factor higher than needed to be protective of 95% of buildings.

Impact of Spatial Variability on Measured Attenuation Factors: To better understand the impact of variability in VOC concentrations on attenuation factors, we used a Monte Carlo approach to simulate the measurement of attenuations factors. For this purpose, we assumed log-normal distribution of VOC concentrations in the subsurface gas with a coefficient of variation of 1.0 and a log-normal distribution of VOC concentration in indoor air with a coefficient of variation of 0.25. The average subsurface VOC concentration was set as 1000 times the average indoor concentration, so that the average true attenuation factor would be 0.001. We then generated 5,000 attenuation factors based on simulated measurements from these populations. The resulting average and upper-percentile attenuation factors are shown in Table 4.6.4.1.

Table 4.6.4.1: Distribution of Measured Attenuation For a Building with a True Attenuation Factor of 0.001, Assuming Log-Normal Spatial Variability.

Sampling Scheme	Attenuation Factor (Error) from 5,000 Iterations			
	Median	Average	90th Percentile	95th Percentile
1 Subsurface / 1 Indoor Air Measurement	0.0014 (1.4x)	0.0022 (2.2x)	0.0044 (4.4x)	0.0062 (6.2x)
3 Subsurface / 3 Indoor Air Measurements	0.0012 (1.2x)	0.0014 (1.4x)	0.0023 (2.3x)	0.0029 (2.9x)
5 Subsurface / 1 Indoor Air Measurements	0.0011 (1.1x)	0.0012 (1.2x)	0.0020 (2.0x)	0.0024 (2.4x)

The Monte Carlo simulation indicates that the variability in VOC concentration will result in a 95th percentile attenuation factor that is 6.2 times higher than the true attenuation factor in a database of attenuation factors based on single subsurface gas and indoor air measurements. It is interesting to note that for assumed log-normal distributions, even the average measured attenuation factor is 2.2 times higher than the true attenuation factor for this sampling scheme. The simulation further indicates that the use of multiple measurements to calculate the attenuation factor will reduce the impact of variability on the upper-percentile attenuation factors. The 95th percentile attenuation factors calculated from three subsurface and three indoor air measurements is only 2.9 times higher than the true value. Because the variability in the subsurface is higher than the variability in indoor air, a sampling scheme of five subsurface and one indoor air measurement yields a 95th percentile attenuation factor only 2.4 times higher than the true value.

The Monte Carlo simulation confirms that spatial variability in VOC concentration can have a large impact on the upper-bound attenuation factor in a database compiled using single paired subsurface and indoor measurements. In the absence of any variation in attenuation between buildings, spatial variability can result in a 95th percentile attenuation factor more than six times the true value. However, the use of multiple measurements to calculate the attenuation factor can significantly reduce the impact of spatial variability. This evaluation suggests that all available data should be used to develop a single attenuation factor for each building evaluated, rather than calculating an attenuation factor for each single paired measurement.

5. Cost Assessment

5.1 Cost Reporting

As a site characterization technology, the key cost components of the demonstration were i) sample point installation, ii) sample collection and analysis, and iii) data analysis and reporting. Costs for each field event are presented in Tables 5.1.1 and 5.1.2. Representative unit costs are presented in Section 5.2

Table 5.1.1: Contractor and Materials Costs.

Cost Category	Sub Category	Sample Event: Altus 1 March 2005	Sample Event: Hill 1 Sept 2005	Sample Event: Hill 2 Mar 2006	Sample Event: Altus 2 Jul 2006	Sample Event: Altus 3 Dec 2006
Project planning and preparation		N/A	N/A	N/A	N/A	N/A
Installation of monitoring points adjacent to building by direct push technology (12 wells and 8 SG points in 3 clusters)	Contractor Costs	$8,700	$8,700	N/A	N/A	N/A
	Materials Costs	$920	$5,100	N/A	N/A	N/A
Installation of monitoring points through foundation (3 Sub-slab pts and 4 deeper SG pts)	Contractor Costs	N/A	N/A	N/A	N/A	N/A
	Materials Costs	$100	$100	N/A	N/A	N/A
Sample collection	Materials, consumables, equipment rental, shipping	$4,100	$5,700	$1,400	$800	$500
Sample analysis	Geotechnical samples (9 samples/blding)	$2,700	$4,800	N/A	N/A	N/A
	Groundwater samples	$1,700	$2,400	$2,900	$1,400	$1,400
	Air/gas sample (Mobile lab)	$20,500	$20,500	N/A	N/A	N/A
	Air/gas sample (Off-site lab)	N/A	$5,800	$22,000	$12,100	$9,900
	Radon	$500	$700	$2,900	$800	$1,000
Data evaluation and reporting	Consumables	$100	$100	$100	$100	$100

Table 5.1.2: Consultant Labor Requirements (Hours)**.**

Cost Category	Sub Category	Sample Event Altus 1 March 2005	Hill 1 Sept 2005	Hill 2 Mar 2006	Altus 2 Jul 2006	Altus 3 Dec 2006
Project planning and preparation	Scientist/ Engineer	170	200	120	100	50
	Technician	20	30	10	40	10
Installation of monitoring points adjacent to building by direct push technology (12 wells and 8 SG points in 3 clusters)	Scientist/ Engineer	50	40	N/A	N/A	N/A
	Technician	40	20	N/A	N/A	N/A
Installation of monitoring points through foundation (3 Sub-slab pts and 4 deeper SG pts)	Scientist/ Engineer	10	20	N/A	N/A	N/A
	Technician	20	40	N/A	N/A	N/A
Sample collection	Scientist/ Engineer	110	100	80	60	60
	Technician	0	0	0	0	0
Sample analysis	Scientist/ Engineer	N/A	N/A	N/A	N/A	N/A
	Technician	N/A	N/A	N/A	N/A	N/A
Data evaluation and reporting	Scientist/ Engineer	400	230	120	110	60
	Technician	130	80	40	30	10

5.2 Cost Analysis

Representative unit costs for each component of the VI investigation program are provided in Table 5.2.1.

Table 5.2.1: Representative Unit Costs for Vapor Intrusion Investigation.

Cost Category	Sub Category	Representative Unit	Representative Unit Cost
Installation of monitoring points adjacent to building by direct push technology	Monitoring well (1" diameter, 10 ft depth w/ 2 ft screen)	monitoring well	$415
	Soil gas point (1/2" diameter, 5 ft depth w/ 2" screen)	soil gas point	$415
Installation of monitoring points through foundation	Sub-slab point (3/16" diameter penetration through foundation w/ fittings installed for sample collection)	sub-slab point	$33
	Soil gas point (4 ft depth, 1" sample point connected to surface by 1/8" tubing)	soil gas point	$27
Sample analysis	Geotechnical samples	soil core	$315
	Groundwater samples (VOCs by Method 8260)	water sample	$100
	Air/gas sample (by Method 8260 in Mobile lab)	air/gas sample	$350
	Air/gas sample (by Method TO-15 at off-site lab)	air/gas sample	$310
	Air/gas sample (by Method TO-15 at off-site lab)	air/gas sample	$340
	Radon (gas sample at off-site lab)	air/gas sample	$100
	Radon (by carbon canister, indoor and ambient air only)	air sample	$25
	SF_6 (by NIOSH Method 6602)	air sample	$95

Note: Representative costs include all materials and labor costs for contractors and laboratory. Representative costs do not include labor costs for consultant oversight, field work, sample collection, data analysis, or reporting.

6. Implementation Issues

6.1 Environmental Checklist

No permits or approvals from regulatory agencies are required for implementation of a VI field program. Underground utility clearance required for the installation of the groundwater and soil gas monitoring points should be obtained from the appropriate authority.

For the purpose of data evaluation, applicable regulatory screening values should be identified from state regulatory guidance. In the absence of applicable state guidance, base policies should guide the selection of appropriate EPA guidance or other applicable sources for vapor intrusion screening values.

6.2 Other Regulatory Issues

Project results have been presented in peer-reviewed publications, conference presentations, and communications with state and EPA regulators. Specific technology transition tools used to communicate the results of our current project include:

Peer-Reviewed Publications:

McHugh T.E., Hammond, D.E., Nickels, T., Hartman, B., 2007, "Use of Radon Measurements for Evaluation of VOC Vapor Intrusion: Method and Application", Manuscript accepted for publication in Environmental Forensics.

Gorder, K., McHugh, T.E., Case, J., Holt, M., 2007, Analysis of Indoor Vapor Intrusion Data from Hill Air Force Base, Utah, Manuscript Submitted for Peer-review to Groundwater Monitoring and Remediation

McHugh, T.E., de Blanc, P.C., and Pokluda, R.J., 2006, "Indoor Air as a Source of VOC Contamination in Shallow Soils Below Buildings" *Soil and Sed. Contam.,* Vol. 15, No. 1, pp. 103-122, January 2006.

McHugh, T.E. Ahmad, F. Connor, J.A., 2004, "Empirical Analysis of Groundwater-to-Indoor-Air Exposure Pathway Based on Measured Concentrations at Multiple Groundwater Impact Sites" *Env. Forensics*. Vol. 5, No. 1, pp. 33-44, March 2004.

McHugh, T. E., J. A. Connor, F. Ahmad, and C.J. Newell, 2003,"A Groundwater Mass Flux Model For Groundwater-To-Indoor-Air Vapor Intrusion", *Paper H-09*, in: V.S. Magar and M.E. Kelley (Eds.), *In Situ and On-Site Bioremediation—2003.* Proceedings of the Seventh International In Situ and On-Site Bioremediation Symposium (Orlando, FL; June 2003). ISBN 1-57477-139-6, published by Battelle Press, Columbus, Ohio, www.battelle.org/bookstore.

Contributions to Regulatory Guidance:

McHugh, T.E, and Lundegard, P.D., 2005, "Use of Cross-Foundation Pressure Gradient for Understanding Vapor Intrusion", to be included in EPA Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils.

Review and Comment on Numerous Draft State Vapor Intrusion Guidance Including Draft Guidance from New York, New Jersey, and Michigan.

Conference Presentations:

McHugh, T.E., T.N. Nickels, I.O'Brien, "Detailed Field Investigation of Vapor Intrusion Processes", Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 2006.

McHugh, T.E., "Indoor Air as a Source of VOC Contamination in Shallow Soil Below Buildings", Southeast Asia Environmental Forensics Conference, Taipei, Taiwan, September 19-20, 2005.

McHugh, T.E., "Vapor Intrusion Investigation Methods", API Petroleum Vapor Intrusion Workshop, Costa Mesa, California, August 17, 2005.

McHugh, T.E., J.A., Connor, "Methods for Characterization of Exposure to Volatile Chemicals Due to Vapor Intrusion:, 2005 NGWA Ground Water and Environmental Law Conference, Baltimore, Maryland, July 21-22, 2005.

McHugh, T.E., J.A., Connor, “Methods for Characterization of Background Indoor Air and Subsurface Vapor Intrusion”, Fourth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 2004.

In addition, after approval of the final report, we will develop a Fact Sheet on cost-effective vapor intrusion investigation methods suitable for distribution to regulators and the regulated community.

6.3 End-User Issues

The results of this vapor intrusion investigation project will benefit other vapor intrusion investigators, managers of corrective action sites with potential vapor intrusion issues, and regulators overseeing vapor intrusion evaluations. As discussed in Section 2 of this report, current state and federal guidance documents on vapor intrusion provide disparate and sometimes contradictory, recommendations for evaluation of the vapor intrusion pathway. As a result, project managers currently face significant uncertainty in planning a vapor intrusion investigation approach. The stepwise screening and field investigation approach will benefit facility managers by providing investigation results that support a defensible evaluation of vapor intrusion. In addition, the use of a consistent investigation approach between buildings and sites will provide comparable data sets that support an increased understanding of the factors contributing to vapor intrusion impacts.

It is important to note that the recommended approach for the evaluation of vapor intrusion impacts may not satisfy all regulatory requirements. Because the variations between vapor intrusion guidance documents, the end user should review the applicable guidance and modify or supplement the recommended approach to ensure that regulatory requirements are satisfied.

7. References

Altshuler, K. B. and D. E. Burmaster (1997). "Soil Gas Modeling: The Need for New Techniques and Better Information." Journal of Soil Contamination **6**(1): 3-8.

ASTM (1994). Emergency Standard Guide for Risk-Based Corrective Action at Petroleum Release Sites, ES38-94.

Barber, C., G. B. Davis, et al. (1990). "Factors Controlling the Concentration of Methane and Other Volatiles in Groundwater and Soil-Gas Around a Waste Site." Journal of Contaminant Hydrology **5**(2): 155-169.

DiGiulio, D., C. Paul, et al. (2006). Assessment of Vapor Intrusion in Homes Near the Raymark Superfund Site Using Basement and Sub-Slab Air Samples, EPA Office of Research and Development.

Elci, A., F. J. Molz, et al. (2001). "Implications of Observed and Simulated Ambient Flow in Monitoring Wells." Ground Water **39**(6): 853-862.

Fischer, M. L., A. J. Bentley, et al. (1996). "Factors Affecting Indoor Air Concentrations of Volatile Organic Compounds at a Site of Subsurface Gasoline Contamination." Environmental Science and Technology **30**(10): 2948-2957.

Folkes, D. J. and P. S. Arell (2003). Vapor intrusion – EPA's new regulatory initiative and implications for industry. American Bar Association's Litigation Section, Environmental Litigation CLE Seminar, Snowmass, Colorado.

Hers, I., R. Zapf-Gilje, et al. (2003). "Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality." Ground Water Monitoring & Remediation **23**(1): 62-76.

Johnson, P. C. and R. Ettinger (1991). "Heuristic Model for predicting the Intrusion Rate of Contaminant Vapors into buildings." Environmenal Science and Technology **25**(8): 1445-1452.

Lahvis, M. A. and A. L. Baehr (1996). "Estimation of Rates of Aerobic Hydrocarbon Biodegradation by Simulation of Gas Transport in the Unsaturated Zone." Water Resources Research **32**(7): 2231-2249.

McAlary, T. and T. Creamer (2006). The Effects of Purge Rate and Volume on Subslab Soil-Gas Samples. The Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California.

McCarthy, K. A. and R. L. Johnson (1993). "Transport of Volatile Organic Compounds Across the Capillary Fringe." Water Resources Research **29**(6): 1675-1683.

McHugh, T. E., J. A. Connor, et al. (2004a). "An Emperical Analysis of the Groundwater-to-Indoor-Air Exposure Pathway: The Role of Background Concentrations in Indoor Air." Environmental Forensics **5**: 33 - 44.

McHugh, T. E., J. A. Connor, et al. (2004b). "Discussion of *'Evaluation of the Johnson and Ettinger Model for Prediction of Indoor Air Quality'*." Ground Water Monitoring & Remediation **24**(2): 139-140.

McHugh, T. E., J. A. Connor, et al. (2003). A Groundwater Mass Flux Model for Groundwater-to-Indoor-Air Vapor Intrusion Seventh International In Situ and On-Site Bioremediation Symposium, Orlando, FL; USA; 2-5 June 2003, Battelle Press, Columbus, Ohio.

McHugh, T. E., P. C. DeBlanc, et al. (2006). "Indoor Air as a Source of VOC Contamination in Shallow Soils Below Buildings." Soil and Sediment Contamination **15**(1): 103-122.

MWH_Americas (2004). Base Wide Sampling and Analysis Plan, Indoor Air Sampling, Project Number: 1970987.14010401.

Nichols, E. M. and T. L. Roth (2006). Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization and Monitoring of "Diving Plumes", American Petroleum Institute.

NJDEP (2006). Vapor Intrusion Guidance. N. J. D. o. E. Protection.

NYDOH (2006). Guidance for Evaluating Soil Vapor Intrusion in the State of New York. C. f. E. H. New York Department of Health.

OSHA (2007). Indoor Air Quality Standards.

PaDEP (2004). Land Recycling Program Technical Guidance Manual- Section IV.A.4. Vapor Intrusion into Buildings from Groundwater and Soil under the Act 2 Statewide Health Standard, Department of Enviromental Protection, Bureau of Land Recycling and Waste Management

Parker, J. C. (2003). "Modeling Volatile Chemical Transport, Biodecay, and Emission to Indoor Air." Ground Water Monitoring & Remediation **23**(1): 107-120.

Paul, C. J. (2007). Loss/Gain of VOCs from Tedlar Bags and Other Sampling Equipment. USEPA Workshop on Vapor Intrusion. San Diego, California.

Richardson, G. M. (1997). "What Research is Needed on the Indoor Infiltration of Volatile Organic Contaminants." Journal of Soil Contamination **6**(1): 1-2.

Ririe, G. T., R. E. Sweney, et al. (1998). A Vapor Transport Model that is Consistent with Field and Laboratory Data. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation Conference, Houston, Texas, Ground Water Association.

Roggemans, S., C. L. Bruce, et al. (2001). Vadose Zone Natural Attenuation of Hydrocarbon Vapors: An Emperical Assessment of Soil Gas Vertical Profile Data, American Petroleum Institute**:** 1-12.

U.S. Air Force (1993). Air Force Policy Directive 91-3, Occupational Safety and Health.

EPA (2000). User's Guide For The Johnson And Ettinger (1991) Model For Subsurface Vapor Intrusion Into Buildings (Revised). O. o. E. a. R. Response.

EPA (2001). Supplemental Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathways, Draft for Comment. O. o. S. Waste.

EPA. (2002, November 29, 2002). "Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)." Retrieved November 11, 2003, from http://www.epa.gov/epaoswer/hazwaste/ca/eis/vapor.htm.

EPA (2004). A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family From Radon (Revised). I. E. Division.

EPA (2007). Superfund Risk Assessment.

WDHFS (2003). Chemical Vapor Intrusion and Residential Indoor Air, Guidance for Environmental Consultants and Contractors, Wisconsin Department of Health and Family Services, Division of Public Health.

Wertz, B. (2006). NYSDEC - NYDOH Study of Temporal and Spatial Variability of VOC in Soil Gas and Indoor Air, New Youk State Department of Enviornmental Conservation.

8. Points of Contact

Point of Contact	Organization	Phone/Fax/Email	Role in Project
Thomas McHugh	Groundwater Services, Inc 2211 Norfolk, Houston,Texas 77098	Ph: 713-522-6300 Fax: 713-522-8010 temchugh@gsi-net.com	Principle Investigator
Dr. Sam Brock	AFCEE 3300 Sidney Brooks Brooks City-Base Texas, 78235	Ph: 210-536-4329 Fax: 210-536-4330 Samuel.Brock@brooks.af.mil	Contracting Officer's Representative
Mr. Kyle Gorder	Hill AFB	Ph: 801-775-2559 Kyle.Gorder@HILL.af.mil	Hill AFB Contact
Mr. Charles Butchee	Altus AFB	Ph: 580-481-7093 Charles.Butchee@altus.af.mil	Altus AFB Contact

Report Submitted by:

Thomas E. McHugh, Project Lead
GSI Environmental Inc.
December 21, 2007

APPENDICES

Appendix A: Summary of Analytical Methods

Appendix B: Quality Assurance Project Plan

Appendix C: Supplemental Figures for Hill AFB and Altus AFB

Appendix D: Summary of Results from Third Altus AFB Event

Appendix E: Example Calculations

Appendix F: Statistical Evaluation

Appendix G: Project Database of Analytical Results

Appendix H: Health and Safety Plan

Appendix I: Federal and State Vapor Intrusion Resources

Appendix J: Response to Reviewer Comments

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix A

Summary of Sample Point Design and Laboratory Analytical Methods

GROUNDWATER SERVICES, INC.

APPENDIX A
LABORATORY ANALYTICAL METHODS

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

Laboratory Analytical Methods

The analytical methods employed in this investigation are standard methods typically employed in environmental investigations and available at commercial laboratories. Further details regarding the various methods are provided in the report text and the Quality Assurance Program Plan included as Appendix B of this report.

Analytical methods utilized in this investigation are summarized in the following table:

Table A.1 Summary of Laboratory Analytical Methods

Constituent / Matrix	Reference Method
Vapor (Organics)	US EPA 8260B (SIM)
Vapor (Organics)	US EPA Method TO-15 SIM
Vapor (Organics)	US EPA Method TO-15
Vapor (Fixed Gases)	ASTM 1945-96
Vapor (SF6)	US EPA 8260B, NIOSH Method 6602
Groundwater (Organics)	US EPA 8260B
Radon (active)	Berelson, 1987 and Mathieu, 1998
Radon (passive)	US EPA #402-R-93-004 079
Geotechnical Analyses	EPA 9100, ASTM D2216, API RP40

References for the analytical methods utilized in this investigation are provided below.

API RP40, Recommended Practice 40, Second Edition, February 1998

ASTM D1945 Standard Test Method for Analysis of Natural Gas by Gas Chromatography

ASTM D2216 Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures

Berelson, W. M., D. E. Hammond, and A. E. Eaton, 1987, A technique for the rapid extraction of radon-222 from water samples and a case study, Radon, p. 271-281 in Graves, B. (ed.) Radon, Radium, and other Radioactivity in Ground Water, Lewis Pub., Chelsea, MI.

Mathieu, G. G., P. E. Biscaye, R. A. Lupton, and D. E. Hammond, 1988, System for measurement of 222Rn at low levels in natural waters, Health Physics, 55, 989-992.

NIOSH Manual of Analytical Methods, 2nd ed., Vol. 5, U.S. Department of Health, Education, and Welfare (NIOSH) Publ. 79-141 (1979).

US EPA, 1993, Protocols for Radon and Radon Decay Product Measurements in Homes, EPA 402-R-92-003, May 1993* this is a corrected document number

GROUNDWATER SERVICES, INC.

APPENDIX A
LABORATORY ANALYTICAL METHODS

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

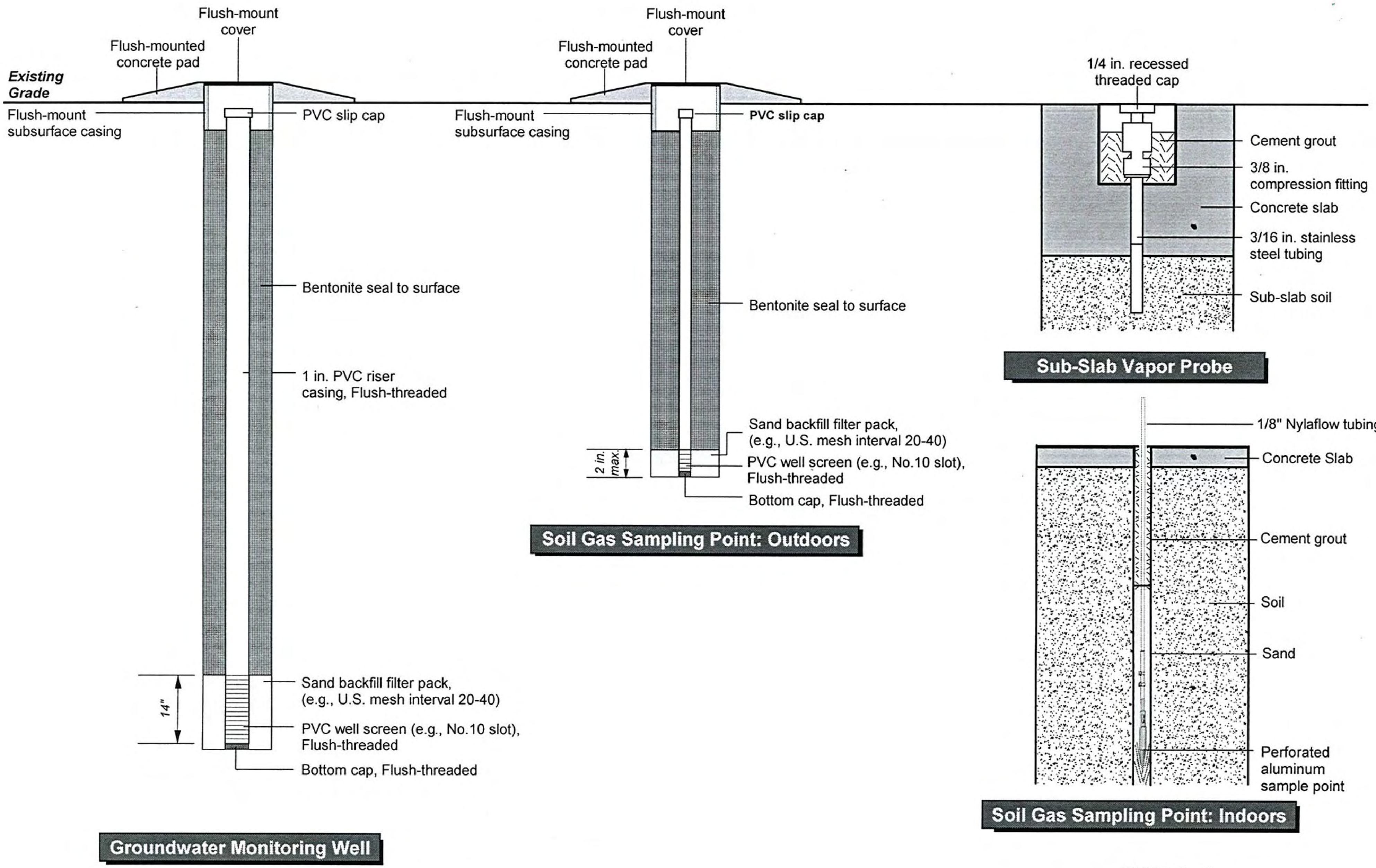
US EPA, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW 846

GSI Job No.: G-2882
Date Issued: 3/2/07
Page 1 of 1

FIGURE A.1: EXAMPLE CONSTRUCTION SPECIFICATIONS FOR SAMPLING POINTS

ESTCP Vapor Intrusion Study

GROUNDWATER SERVICES, INC.

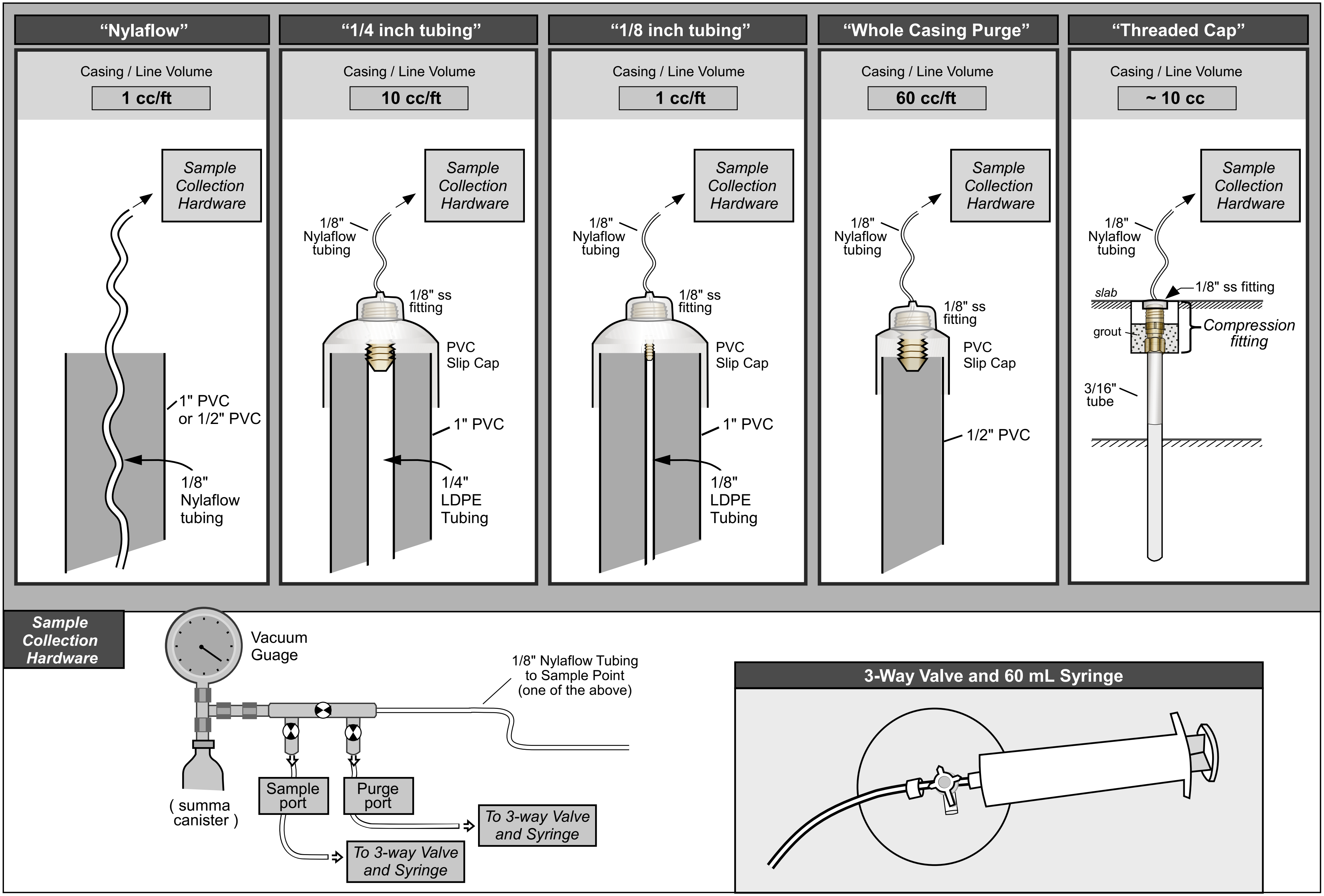


Not to Scale

FIGURE A.2: SAMPLE COLLECTION METHODS

ESTCP Vapor Intrusion Study

GROUNDWATER SERVICES, INC.



July 31, 2007

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix B

Quality Assurance Project Plan (QAPP)

GROUNDWATER SERVICES, INC.

QUALITY ASSURANCE PROJECT PLAN

Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

GROUNDWATER SERVICES, INC.

TABLE OF CONTENTS

GROUNDWATER SERVICES, INC.

TABLES

GROUNDWATER
SERVICES, INC.

LIST OF ACRONYMNS

ASTM	American Society of Testing Materials
bgs	Below ground surface
CCC	Calibration Check Compound
CMS	Corrective Measures Study
DO	Dissolved Oxygen
DQO	Data Quality Objective
ft	Feet
GC/MS	Gas Chromatograph/Mass Spectrometer
HASP	Health and Safety Plan
IDL	Instrument Detection Limit
lb	Pounds
LCS	Laboratory Control Sample
LIMS	Laboratory Information Management System
LTO	Laboratory Task Order
mg	Milligram
MDL	Method Detection Limit
mL	Milliliter
MS	Matrix Spike
MSD	Matrix Spike Duplicate
MQL	Method Quantitation Limit
ng	Nanogram
NIST	National Institute of Standards and Testing
OVA	Organic Vapor Analyzer
PE	Performance Evaluation
PCMT	Potential Corrective Measure Technology
PPB	Parts Per Billion
PPM	Parts Per Million
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
RF	Response Factor
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
RWBS	Reagent Water Blank Spike
SOP	Standard Operating Procedure
SPCC	System Performance Check Compound
TCL	Target Compound List
µg	Microgram
µL	Microliter
USEPA	United States Environmental Protection Agency
VOA	Volatile Organic Analysis
VOC	Volatile Organic Compound
VTSR	Validated Time of Sample Receipt

GROUNDWATER SERVICES, INC.

1.0 PROJECT DESCRIPTION

1.1 Project Overview

This Quality Assurance Project Plan (QAPP) has been prepared for the Detailed Field Investigation of Vapor Intrusion Processes to be conducted by Groundwater Services, Inc. (GSI). The report that accompanies this QAPP describes the project background and investigation objectives, including the site description and history, the project objectives, the sample network design and rationale, and the project schedule.

This QAPP describes data quality objectives (DQOs) as well as the field and laboratory procedures to be implemented in order to fulfill the project objectives. This QAPP was prepared in general accordance with applicable U.S. Environmental Protection Agency (EPA) guidance.

1.2 Objective of the QAPP

The general objective of quality assurance is to collect defensible environmental data of known quality that is adequate for the intended use of the data. To accomplish this objective, data quality objectives (DQOs) have been developed for the Vapor Intrusion Study. DQOs are qualitative and quantitative statements which clarify the study objectives, define the most appropriate types of data to collect, determine the most appropriate conditions from which to collect data, and specify acceptable decisions regarding the data's usage (USEPA 1994a). The DQO planning process is a tool to determine which type, quality, and quantity of data will be sufficient to support the overall project objectives.

2.0 PROJECT ORGANIZATION AND RESPONSIBILITY

2.1 Project Organizational Chart

GSI has overall responsibility for implementation of the Demonstration Plan. H&P Mobile Geochemistry will provide on-site analysis of vapor samples, Columbia Analytical Services will provide laboratory services for analysis of vapor samples, Severn Trent Laboratories, Inc., in Houston, Texas will provide laboratory services for analysis of groundwater samples, Doug Hammond at the University of Southern California will provide laboratory services for analysis of radon, and PTS Geolabs, Inc. (PTS), in Houston, Texas, will analyze soil cores for physical properties. Responsibilities for project management, quality assurance, laboratory, and field personnel are defined below.

2.2 Management Responsibilities

GSI Principal Investigator: The GSI Principal Investigator (PI) will be responsible for implementing the project. The primary function of the PI will be to ensure that technical,

financial, and scheduling objectives are achieved. The PI, supported by the GSI Project Manager and other GSI personnel will:

- Define project objectives and develop a detailed demonstration plan schedule;
- Establish project policy and procedures to address the specific needs of the project;
- Acquire and apply resources as needed to ensure performance within budget and schedule constraints;
- Orient field personnel and support staff to the project's special considerations;
- Review the work performed on each task to ensure quality, responsiveness, and timeliness;
- Review and analyze work performed relative to planned requirements and authorizations;
- Approve reports and deliverables before submittal to ESTCP;
- Retain ultimate responsibility for preparation and quality of interim and final reports; and
- Represent the project team at meetings.

GSI Health and Safety Officer: The GSI Health and Safety Officer will be responsible for overall health and safety practices associated with the field work. Specific functions and duties will include the following tasks:

- Establish the requirements of the project Health and Safety Plan (HASP);
- Arrange or conduct audits of field activities to ensure that proper health and safety procedures are being used;
- Communicate with the PI, GSI Technical Staff, and GSI Field Technical Staff concerning project issues related to health and safety.

GSI QA Manager: The GSI QA Manager will report directly to the PI and will be responsible for reviewing QA documentation to evaluate compliance with sampling and analytical procedures.

GSI Technical Staff: The GSI Technical Staff will assist the PI in field activities such as collecting soil samples and soil cores, performing field analyses, and recording field measurements and office activities such as data review and report development. GSI Technical Staff will be familiar with relevant project reports and plans including the Demonstration Plan, the QAPP, and the Health and Safety Plan.

H&P Project Manager: The H&P Project Manager will report to the PI. The H&P Project Manager will be responsible for ensuring laboratory resources are available as needed for the project and will provide oversight of final laboratory reports.

H&P QA Manager: The H&P QA Manager will have overall responsibility for data generated in the laboratory. The H&P QA Manager will be independent of the laboratory production responsibilities, but will communicate data issues through the H&P Project Manager. In addition, the H&P QA Manager will

- Monitor the day-to-day quality of the laboratory data.
- Maintain and review all quality control data.

GROUNDWATER SERVICES, INC.

- Conduct internal performance and system audits to ensure compliance with laboratory protocols.
- Review and maintain updated Standard Operating Procedures (SOPs).
- Prepare Performance Evaluation reports and corrective action reports.

H&P Technical Staff: The H&P Technical Staff will be responsible for sample analysis and identification of necessary corrective actions. Staff members will report directly to the H&P Project Manager.

Columbia Analytical Services Project Manager: The CAS Project Manager will report to the PI. The indoor air lab Project Manager will be responsible for ensuring laboratory resources are available as needed for the project and will provide oversight of final laboratory reports.

Columbia Analytical Services QA Manager: The CAS QA Manager will have overall responsibility for data generated in the laboratory. The indoor air lab QA Manager will be independent of the laboratory production responsibilities, but will communicate data issues through the indoor air lab Project Manager. In addition, the indoor air lab QA Manager will

- Monitor the day-to-day quality of the laboratory data.
- Maintain and review all quality control data.
- Conduct internal performance and system audits to ensure compliance with laboratory protocols.
- Review and maintain updated Standard Operating Procedures (SOPs).
- Prepare Performance Evaluation reports and corrective action reports.

Columbia Analytical Services Technical Staff: The CAS Technical Staff will be responsible for sample analysis and identification of necessary corrective actions. Staff members will report directly to the indoor air lab Project Manager.

STL Project Manager: The STL Project Manager will report to the PI. The STL Project Manager will be responsible for ensuring laboratory resources are available as needed for the project and will provide oversight of final laboratory reports.

STL QA Manager: The STL QA Manager will have overall responsibility for data generated in the laboratory. The STL QA Manager will be independent of the laboratory production responsibilities, but will communicate data issues through the STL Project Manager. In addition, the STL QA Manager will

- Monitor the day-to-day quality of the laboratory data.
- Maintain and review all quality control data.
- Conduct internal performance and system audits to ensure compliance with laboratory protocols.
- Review and maintain updated Standard Operating Procedures (SOPs).
- Prepare Performance Evaluation reports and corrective action reports.

GROUNDWATER SERVICES, INC.

STL Technical Staff: The STL Technical Staff will be responsible for sample analysis and identification of necessary corrective actions. Staff members will report directly to the STL Project Manager.

PTS Project Manager: The PTS Project Manager will report to the GSI Project Manager. The PTS Project Manager will be responsible for ensuring laboratory resources are available to Solutia as needed for the project and will provide oversight of final laboratory reports.

PTS QA Manager: The PTS QA Manager will have overall responsibility for data generated in the laboratory. The PTS Project Manager will be independent of the laboratory production responsibilities, but will communicate data issues through the PTS Project Manager. In addition, the PTS Project and QA Manager will

- Monitor the day-to-day quality of the laboratory data.
- Maintain and review all quality control data.
- Conduct internal performance and system audits to ensure compliance with laboratory protocols.
- Review and maintain updated SOPs.
- Prepare Performance Evaluation reports and corrective action reports.

PTS Technical Staff: The PTS Technical Staff will be responsible for sample analysis and identification of necessary corrective actions. Staff members will report directly to the PTS Project and QA Manager.

3.0 QUALITY ASSURANCE OBJECTIVES FOR MEASUREMENT DATA

In order to provide technically sound and defensible results, data quality objectives (DQOs) have been developed for the laboratory analysis of VOC concentrations and soil core properties during the study. DQOs have been developed with a consideration of the level of detail available in the reference method to be used for analysis. Consequently, detailed DQOs have been developed for data produced during analysis of VOC concentrations in accordance with USEPA SW-846 methods, and a limited set of DQOs has been developed for data produced during analysis of radon and soil core properties properties by API or ASTM methods.

For the analysis of VOC concentrations by USEPA SW-846 and TO-15 methods, quantifiable DQOs have been developed for accuracy, precision, and completeness. Acceptable levels of non-quantifiable data quality parameters (i.e., representativeness and completeness) will be assured through the proper implementation of field and laboratory SOPs.

Definitions, development, and interpretation of DQO parameters and detection limits are presented below.

GROUNDWATER SERVICES, INC.

3.1 Precision

3.1.1 Definition

Precision is a measure of the degree to which two or more measurements are in agreement as a result of repeated application of a process under specific conditions. The overall precision and reproducibility of a measurement system is affected by variations introduced by sampling and analysis.

3.1.2 Field Precision Objectives

Field precision will be assessed by collecting and analyzing field duplicates at a minimum rate of 1 duplicate per 20 analytical samples. The field precision objective for laboratory analysis of VOCs is ±30% relative percent difference (RPD) between field duplicates. Objectives for field precision of radon samples have been established by requiring a field duplicate sample be collected during the sampling event at a frequency of 1 duplicate per 10 samples. Field precision is demonstrated by an RPD of ± 30% or 0.5 pCi/L, whichever is larger. This objective takes into account the accuracy limitations of the analytical method (Mathieu and Berelson). No other analyses will have field precision objectives.

3.1.3 Laboratory Precision Objectives

Laboratory precision objectives for laboratory QC samples are listed on Table 2.1. Precision objectives for analysis of VOCs are listed on Table 2.2. In accordance with method requirements, laboratory precision will be assessed by analysis of various duplicates sets (e.g., laboratory duplicates, reagent water blank spike duplicates, matrix spike duplicates).

3.2 Accuracy

3.2.1 Definition

Accuracy is the degree of agreement between an observed value (or an average of several values) and an accepted reference value. Deviations from standard values result from cumulative inconsistencies in the measurement system. Potential sources of variance include (but are not limited to) sample collection, preservation, and handling procedures; matrix effects, and analytical procedures.

3.2.2 Field Accuracy Objectives

Accuracy in the field will be assessed through the use of trip blanks and through the adherence to all sample handling, preservation, and holding times. One trip blank will be submitted for laboratory analysis each day that samples are submitted for analysis of VOC concentration (see Table 2.4). Accuracy objectives for field samples will be met if concentrations of VOCs are below project quantitation limits in the trip blank. The collection of an ambient radon sample has also been added to the project DQOs in place

of a traditional field blank sample. This sample will provide information on the normally occurring radon concentration in the outdoor air at the sampling location, providing a comparison to indoor results.

3.2.3 Laboratory Accuracy Objectives

In accordance with method requirements, laboratory accuracy will be assessed by the analysis of various spike samples (e.g., spikes, matrix spikes, control standards, interference check samples, standard reference samples, and surrogates). Where required by the method, an LCS will consist of a standard purchased from a source other than that for the calibration standards. The use of an LCS will be based on the availability of a USEPA, National Institute of Standards and Testing (NIST), or commercially certified LCS. Accuracy objectives for laboratory samples will be met if percent recoveries fall within the limits shown on Tables 2.2 and 2.3.

3.3 Completeness

3.3.1 Definition

Completeness is expressed as the percentage of valid data points obtained from a measurement system or method.

3.3.2 Field Completeness Objectives

Field completeness will be assessed for target parameters by comparing the number of valid field samples to the total number of field samples collected. The validity of field samples will be assessed by comparison of documented field practices to requirements of this QAPP and the accompanying Demonstration Plan. The completeness objective for field samples will be at least 90%.

3.3.3 Laboratory Completeness Objectives

The results of a laboratory analysis will be considered valid if predetermined data quality objective standards are met or exceeded for precision and accuracy. Completeness requirements for other analytical parameters will be based on available QC data provided in accordance with applicable API and ASTM methods. Laboratory completeness will be assessed for VOCs by comparing the number of valid measurements to the total number of measurements. Completeness for laboratory samples will be at least 95%.

3.4 Representativeness

3.4.1 Definition

Representativeness is a qualitative parameter that expresses the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition. As such,

representativeness describes whether samples collected, or the aliquots selected by the laboratory for analysis, are sufficient in number, type, location, frequency, and size to be characteristic of the substance analyzed.

3.4.2 Measures to Ensure Representativeness of Field Data

Field representativeness will be satisfied by following the sample collection procedures specified in the QAPP. In addition, collection of duplicate samples will provide a measure of the variability of analyte present in a particular sample volume.

3.4.3 Measures to Ensure Representativeness of Laboratory Data

Representativeness in the laboratory will be ensured by using the proper analytical procedures, meeting sample holding times, and analyzing and assessing field duplicates.

3.5 Comparability

3.5.1 Definition

Comparability is an expression of the confidence with which one data set can be compared with another.

3.5.2 Measures to Ensure Comparability of Field Data

Comparability of field data will be assured by adhering to standard sampling procedures described in the QAPP, using traceable calibration standards; using standard measurement and reporting units; and using the pre-determined acceptance criteria for precision and accuracy presented in this QAPP.

3.5.3 Measures to Ensure Comparability of Laboratory Data

Comparability of laboratory data will be assured by adhering to standard analytical procedures described in this QAPP, using traceable calibration standards; using standard measurement and reporting units; and using pre-determined acceptance criteria for precision and accuracy.

3.6 Level of Quality Control Effort

3.6.1 Level of Field Quality Control Effort

Requirements for collection of field quality control samples are provided on Table 2.4. Field precision will be assessed by collecting and analyzing field duplicate samples. For groundwater samples, matrix effects on the sample analysis will be assessed through the collection and analysis of matrix spikes and duplicates. Additional sample volumes will be collected in order to prepare MS/MSD sets for water samples.

Sampling accuracy will be assessed by collecting and analyzing field duplicates. Results from the analysis of trip blanks will be used to assess the potential for sample contamination during sample shipment, handling, and storage.

3.6.2 Level of Laboratory Quality Control Effort

Requirements for laboratory QC samples are provided on Table 2.1. Results from method blank samples for all constituents analyzed will be reviewed to assess potential sources of contamination associated with laboratory procedures. Laboratory method blanks will be prepared and analyzed at a frequency of 1 per sample batch (i.e., each group of samples prepared and analyzed as a group, not to exceed 20 samples).

Results for MS/MSD pairs will be reviewed to evaluate the effect of the sample matrix on the sample preparation and measurement methodology. MS/MSD sets will be analyzed at a frequency of 1 per sample batch (i.e., each group of samples prepared and analyzed as a group, not to exceed 20 samples). Recovery and relative percent difference targets for MS/MSD sets are listed on Table 2.2.

Accuracy for the analysis of volatile organic compounds will be assessed by evaluating the recoveries of surrogate compounds spiked into all samples. Laboratory control limits for surrogates are provided on Table 2.3 of this QAPP.

4.0 SAMPLING PROCEDURES

Field sampling procedures employed during the Vapor Intrusion Study will be consistent throughout the project, thus providing data representative of site conditions, comparability with analytical considerations, practicality, and simplicity. Procedures for installation of soil borings and all aspects of collection, preservation, and transport of soil core samples are provided in the Demonstration Plan or this QAPP.

Method specified sample containers, preservatives, and holding times are summarized for air and water samples on Table 3.

4.1 Groundwater Sampling Procedures

Low-Flow Sample Collection

Sampling should be conducted according to low-flow (minimal drawdown) procedures. Groundwater will be purged and samples collected using a peristaltic pump and dedicated polyethylene and Teflon tubing. Field indicators, which includes, pH, temperature, and specific conductance will be recorded every 3-5 minutes. Once groundwater field indicator parameters have stabilized, groundwater samples will be collected. Groundwater field indicator parameters should be considered stabilized when three sets of consecutive readings have been obtained for pH (+/- 0.2 standard units), temperature (+/- 10%), and specific conductance (+/- 3%).

Sampling Equipment

Groundwater monitoring wells will be sampled, to the extent practicable, using dedicated equipment, such as a dedicated bailer, peristaltic pumps with dedicated down-hole tubing, or other suitable sampling equipment. Equipment made from inert, non-reactive materials such as Teflon®, stainless steel, Tygon®, or other suitable materials will be used. The use of dedicated equipment for groundwater collection will minimize the need for decontamination of sampling equipment between sampling episodes and the potential for cross-contamination. In the event that non-dedicated equipment is used, that equipment will be cleaned as described above prior to use in each well.

Groundwater Sample Handling

Groundwater samples will be collected and handled to minimize the potential for cross-contamination, loss of volatile constituents, or other interferences. Sampling personnel will wear clean latex, nitrile or other chemical resistant, non-reactive gloves when handling sampling equipment and containers, and will minimize contact with the sampled groundwater. Care will be taken to prevent contact of the bailer, cord, or other down-hole equipment with the ground or other potential sources of sample contamination. Gloves will be changed between sampling locations.

Groundwater samples will be collected using techniques appropriate for the analytes to be tested as specified by USEPA SW-846 methods.

If pumps are used to collect samples, the sample will be collected at low flow rates (e.g., <0.3 gpm). When bailers are used, they will be lowered into the well and decanted carefully to minimize agitation. Samples for analysis of volatile compounds will not be collected using techniques which can aerate the samples.

As specified by USEPA SW-846, collected samples will be retained in wet ice coolers pending transport to the laboratory with adequate ice to maintain samples at a temperature of approximately 4°C.

On-Site Testing of Temperature, Specific Conductance, and pH

A sample of groundwater will be collected for analysis of temperature, specific conductance, and pH at the well site. Equipment used to measure these parameters will be calibrated beforehand. Equipment out of calibration by 10% or more will not be used for field measurements. Laboratory measurements of specific conductance and/or pH made within 24 hours of sample collection may augment or replace field measurements, in the event of field instrument malfunction or other factors.

Purge volume information, field parameter test results, and other sample information will be recorded on a field sample form.

4.2 Vapor Sampling Procedures

Purging prior to sampling

GROUNDWATER SERVICES, INC.

The test points designated for soil gas sampling will be fitted with a sealing device to prevent atmospheric air from entering the well casing. Prior to sampling, a pre-determined volume of air will be purged from the casing to ensure that the soil gas sample is representative of vapors associated with the soils in the vadose and are not being influenced by stagnant air in the casing. Depending on the porosity of the vadose soils, a vacuum may be created in the casing during the purging process. Care should be taken to purge slowly enough that the seal on the casing remains intact and atmospheric air is not allowed into the casing.

Air and vapor samples potentially containing high concentrations of VOCs (i.e., >50 ug/m3 will initially be analyzed directly by Gas Chromotography (GC). Samples containing less than 50 ug/m3 of our target compounds (i.e., PCE, TCE, or 1,2-DCE) will be re-analyzed by TO-15. The GC will quantify only our target compounds, while the TO-15 analysis will quantify all compounds on the standard TO-15 analyte list (Table 1.2).

<u>High level screening sampling</u>

After purging, a sample will be collected with a GC syringe and injected directly onto a GC column to analyze for high level i.e., >50 ug/m3, selected target VOCs. The sample will be collected through a fitting that maintains an airtight seal on the casing. If the detected concentrations of selected compounds are below the reporting limits of the direct GC method, i.e., 50 ug/m3, sample will be collected in a Summa canister for TO-15 analysis. Screening will be conducted on-site during the initial investigation at each site using the H&P mobile laboratory.

<u>Low level sampling</u>

Low level samples will be collected in Summa canisters that have been appropriately purged and charged with negative pressure (vacuum). Summa canisters will be individually certified clean before use, batch certified Summa canisters are not acceptable for this project. The Summa canisters will be connected to the sampling point by means of a sampling train with a valve that prevents atmospheric air from entering the casing. The Summa canister will be connected to the valve, the valve opened and then the valve on the Summa canister opened to draw sample into the canister. When sampling is complete, the valve on the Summa canister will be closed, the valve on the sample train will be closed and then the canister will be disconnected from the sampling train.

In addition, a tracer gas (1,1-di-fluoroethane, pentane, or SF6) will be released into the sampling vaults during sample collection to evaluate the potential for infiltration of ambient air into the soil gas samples.

4.3 Radon Sampling Procedures

<u>Activated Charcoal Canisters</u>

Radon gas is sampled in a passive process with the use of activated charcoal contained in air-tight metal canisters. When the sample is ready to be collected, the canister is unsealed and left exposed to the ambient atmosphere for a set period of time. At the end of the sampling period the canister is sealed and the exposure time noted for use by the laboratory. The sealed canister is submitted to the laboratory for analysis.

Vacuum Cell

Radon gas is sampled in an active process in which a glass sampling cell under vacuum is attached to the sampling line or port. The valve on the cell is opened allowing the sample to be collected and then closed to seal the cell. The cell is submitted to the laboratory as soon as possible for analysis.

Tedlar Bag

Radon gas is sampled in an active process in which a gas-tight syringe is attached to the sampling line or port. The valve on the syringe is opened allowing the sample to be collected and then closed to seal the syringe. The vapor in the syringe is then transferred into a tedlar bag for transport and analysis. The tedlar bag is submitted to the laboratory as soon as possible for analysis.

5.0 CUSTODY PROCEDURES

In order to generate defensible analytical data, sample custody procedures will be implemented for handling environmental samples and associated records during sample collection, shipment, transfer, and storage. These procedures will support the authenticity of sampling data by tracing samples from the time of collection, through analysis, data generation, and report preparation.

A sample is considered to be within custody if the item is i) in one’s physical possession; or ii) in one’s view after being in one’s physical possession; or iii) in a locked receptacle after being in one’s physical possession; or iv) in a designated secure area. Procedures described below address custody during field sample collection, laboratory analysis, and file storage.

When completing written records to document sample custody, errors will be corrected by drawing a single line through the error, re-entering the correct information, and initialing and dating the correction.

5.1 Field Custody Procedures

Sample containers provided by the laboratory for this project will be shipped by common carrier or other suitable method in sealed coolers to a location designated by the PI. The laboratory will include a shipping form/laboratory chain-of-custody listing containers shipped and the purpose of each container. Containers will be considered in the

GROUNDWATER SERVICES, INC.

custody of the laboratory until received by GSI or a designated representative. Upon receipt, the shipment will be checked to verify that all containers are intact. The containers will be maintained in the custody of the receiver in a clean, secure area until used for sample collection.

Procedures described below address custody during field sample collection, laboratory analysis, and file storage for the data collected in study.

- Field sampling personnel will be personally responsible for the care and custody of the samples until transferred or properly dispatched.
- Sample bottles and vessels will be labeled with sample numbers and locations at the time of sample collection.
- Sample labels will be completed with permanent ink.

After collection, field sampling personnel will maintain sample custody in accordance with the following procedure:

1. The sample label affixed to the container will be inspected to confirm that all of the required information has been provided.
2. If appropriate, the sample container will be sealed in a zip-lock plastic bag, wrapped in bubble pack, and packed in a wet-ice or dry-ice cooler in a manner to minimize shifting or movement.
3. For each set of samples sent to the laboratory, a triplicate chain-of-custody form will be completed. Information on the chain-of-custody form and the sample container labels will be checked against the field logbook entries and the samples will be recounted. The information contained on the chain-of-custody form will include the following:
   - Site name and address or location;
   - Project number;
   - Date of sample collection;
   - Name of sampler responsible for sample submittal;
   - Identification of samples that accompany the form including
   - Field ID number,
   - Number of samples,
   - Date/time collected,
   - Sample container type, volume, preservative,
   - Parameters/methods of interest,
   - Data level requirement (e.g., Level II),
   - Comments about sample conditions;
   - Signature of person relinquishing custody and signature of person accepting custody, plus date and time; and
   - Identification of common carrier.
4. If a commercial courier service (e.g., Federal Express) transports the samples to the laboratory, the chain-of-custody form will be signed by a member of the field team, and a

copy retained by the field team. The remaining two copies of the form will be sealed in a zip-type plastic bag and placed in the cooler with the samples. The cooler will be sealed with packaging tape. Package routing documentation maintained by the courier service will serve as chain-of-custody documentation during shipment, because commercial couriers do not sign chain-of-custody forms.

5. If samples are picked up by a laboratory representative, a member of the field team will sign the chain-of-custody record indicating that the samples have been transferred to the lab courier. The lab courier will also sign the form, indicating that the samples have been transferred to his or her custody. One copy of the chain-of-custody form will be retained by the field team and the remaining two copies will be sealed in a zip-type plastic bag and placed in the cooler chest with the samples.

5.2 Laboratory Custody Procedures

For the Vapor Intrusion Study, normal laboratory custody procedures will be implemented. Samples received and logged into the laboratory will remain in the custody of STL or PTS Labs personnel at the laboratory until disposal.

5.2.1 Sample Receipt and Inspection

Upon arrival at the laboratory, samples will immediately be taken to the sample receiving area and logged into the laboratory sample registry in which the date and time of sample receipt will be recorded. The shipping container will be opened immediately and the temperature of the shipping container measured and documented on the appropriate laboratory form.

Shipping containers having custody seals will be inspected for integrity upon arrival at the laboratory. The appropriate space on the chain-of-custody (i.e., "custody intact") will be checked "Y" for yes or "N" for no. If tampering of the custody seal is apparent, the sample custodian will immediately contact the Laboratory Project Manager who will be responsible to notify the GSI Project Manager.

Information on the chain-of-custody form will be checked against the sample labels and then signed by the sample custodian. The sample custodian will also inspect sample containers for leakage. A multi-phase sample which has leaked will not be acceptable for analysis, because the sample integrity has been altered. Samples in plastic containers appearing to bulge or evolve gas will be treated with caution, because toxic fumes or material of an explosive nature may be present. Discrepancies between information on sample labels and information provided on the chain-of-custody form or broken/altered samples will be resolved with the Laboratory Project Manager before the sample is assigned for analysis.

If a custody problem occurs, the sample custodian will initial the "NOTIFIED CLIENT" blank on the sample registry and immediately notify the Laboratory Project Manager. The Laboratory Project Manager will resolve custody problem as soon as practical and notify the GSI Project Manager, if necessary. After notification, an initialed note will made on the custody form which states who was notified, reason for notification, and resolution, if applicable.

5.2.2 Internal Tracking and Numbering

The sample custodian or designee will have responsibility for maintaining sample receipt logbooks, assigning a project log number to the samples, signing the chain-of-custody form, reporting inconsistencies to the Laboratory Project Manager, and distributing samples to the laboratory sections in accordance with applicable analytical procedures. The laboratory section sample custodian is responsible for ensuring that samples are placed in storage, for monitoring conditions in sample storage areas, and maintaining records for chain-of-custody within the laboratory. The Project Manager or designee is responsible for initiating paperwork for report files and analytical worksheets and logging samples into the Laboratory Information Management System (LIMS), if applicable.

Each sample will be assigned a unique laboratory sample number at the time of log-in to facilitate tracking of samples, extracts, and digests during analysis. The laboratory sample number will be recorded on the chain-of-custody form and Sample Registry, and logged into the computerized LIMS, if applicable. Any accompanying paper work will be placed in a project file until the order is completed. The laboratory project identification number will be recorded on all containers submitted in the project shipment.

After initiating a new log-in number, the Project Manager or designee will enter electronically or otherwise record relevant sample information, as follows:

- Laboratory sample number
- Client project identification
- Date received/date due
- Matrix/sample identification
- Date and time of sample collection
- Storage location/container size/container type/preservative
- Analyses required
- Problems/special instructions

After assignment of the project identification number, samples will be labeled to identify the project number and sample designation. The samples will then be dispersed to the appropriate sample storage area. As required, sample storage temperature logs will be maintained for storage refrigerators or freezers to assure maintenance of proper sample temperature throughout the analyses.

5.2.3 Internal Laboratory Custody Transfers

An internal laboratory chain-of-custody record is not required when samples are transferred to different areas of the laboratory.

GROUNDWATER SERVICES, INC.

5.2.4 Laboratory Storage Areas

As required, samples and extracts will be stored in uniquely identified refrigerated storage units located in secure areas of the laboratory. Samples are logged into the various department storage areas prior to preparation, analysis, or disposal. Samples to be analyzed for volatile organic compounds (VOCs) will be segregated from other samples. Samples will be stored separately from standards.

On a daily basis, the sample custodian or appropriate designee will measure and record the temperature of each refrigerator or freezer used for sample storage. Temperature records will be reviewed on a monthly basis to note any trends or inconsistencies. For samples to be analyzed for VOCs, the acceptable range for sample storage is 4±2°C. The sample custodian will notify the Laboratory Project Manager of any refrigerator temperature problem which cannot be corrected by simple thermostat adjustment. A list of emergency repair numbers will be attached to the exterior of each refrigeration unit.

5.2.5 Requirements for Sample Disposal

Unless requested otherwise, samples will be disposed of as soon as holding times have expired or 30 days after results are reported to GSI.

If analyses performed on composite aqueous samples meet public sewer system discharge criteria, the composite samples will be neutralized, if necessary, and discharged into the public sewer system. Tests performed on the composite samples must demonstrate that the levels of contaminants present do not exceed hazardous characteristics.

5.2.6 Inter-Laboratory Custody Transfers

Under normal circumstances, samples will be analyzed by H&P Mobile Lab, a suitable indoor air lab, STL Houston in Houston, Texas, or PTS Geolabs in Houston, Texas. In the event of a natural disaster (e.g., a hurricane), samples to be analyzed by STL Houston may be sent to another Severn Trent Laboratory for analyses. When samples are transferred to another laboratory in the Severn Trent network, a chain-of-custody form will be initiated at shipping time by the sample custodian. A completed and signed fax of the Interdivisional Shipping Log will be sent to the receiving division custody department. This inter-laboratory chain-of-custody form will be sent with the samples and upon arrival at the division laboratory, laboratory custody procedures described above will be followed.

5.2.7 Data Archiving, Storage and Final Evidence File

Laboratory records will be maintained in a secure area with other associated project records. Hard copies of final reports, chain-of-custody forms, and any ancillary documentation pertinent to the project will be stored in a secured storage area. Analytical data stored in a LIMS will be maintained under a high level of data security by the use of passwords and file access/lock codes. At the end of a project, all custody

GROUNDWATER SERVICES, INC.

forms will be returned to the laboratory project manager. Copies of custody information will be retained in the reporting laboratories' client files. Hard copies of reports, chain-of-custody forms and sample registries will be kept by the laboratory for a period of three years. Raw data and bench data files will be kept by the laboratory for a period of three years.

5.3 Final Evidence Files

A Final Evidence File will be developed for the Vapor Intrusion Study data including the following items: reports, field notes, laboratory reports, signed chain-of-custody forms, sampling procedures, and any other pertinent documents, including, but not limited to the following items:

- Standard operating procedures
- Field notes and field logbooks
- Laboratory reports and data deliverables
- Signed chain-of-custody documentation (tags, air bills, signed forms)
- Photographs
- Drawings
- Soil boring logs
- Data validation reports
- Data assessment reports
- Project reports

These items will be stored in a cabinet at the GSI office and access limited to concerned project personnel. The Final Evidence File will be maintained at this location until the conclusion of the project. The GSI Project Manager will serve as the file custodian for the Vapor Intrusion Study.

6.0 CALIBRATION PROCEDURES AND FREQUENCY

This section describes the calibration procedures and the frequency at which these procedures will be performed for both field and laboratory instruments.

6.1 Field Instrument Calibration

The field instruments to be used for this project will be pH, temperature, turbidity and specific conductivity meters. These instruments will be maintained and calibrated with sufficient frequency and in such a manner that accuracy and reproducibility of results will be consistent with the manufacturer's specifications.

Equipment will be examined prior to conducting field activities to verify proper operating condition. This will include review of the appropriate SOP and equipment maintenance schedule to ensure that required maintenance is completed. Field notes from previous

sampling trips will be reviewed for notation of prior equipment problems, and to ensure that necessary repairs to have been completed.

Calibrations will be documented in the field logbook and will include the date/time of calibration, name of person performing the calibration, reference standards used, temperature at which readings were taken, and the readings. Multiple readings on the one sample or standard, as well as readings on replicate samples, will likewise be documented. Internally calibrated field instruments failing to meet calibration/check-out criteria will be returned to the manufacturer for service and an alternate instrument will be used. The accuracy and traceability of reference standards used for field instrument calibration will be documented by recording the manufacturer's name and the standard lot number in the instrument calibration log book.

6.2 Laboratory Instrumentation Calibration

The laboratory will employ specific procedures for the operation and calibration of analytical instruments in order to facilitate optimum instrument performance, thereby generating data of acceptable accuracy and precision. Prior to initiating sample analysis, laboratory instruments will demonstrate acceptable performance with respect to applicable standards from the manufacturer or selected reference methods (i.e., USEPA, API, or ASTM).

6.2.1 Storage of Standards

As soon as practical after receipt, standards will be transferred to a designated storage area in the laboratory. Volatile standards will be stored in a freezer; semi-volatile standards at room temperature; and other commercially purchased stock standards at 4°C, in a freezer, or at room temperature, as appropriate. Organic standards will be stored separately from samples. Certification sheets will be kept on file within each lab division and stored for future reference.

6.2.2 Traceability of Standards

Standards used for calibration of instrumentation used in analyzing samples for the Vapor Intrusion Study will be NIST traceable, EPA A2LA certified, or obtained from another appropriate source. Records will be maintained to verify the traceability of all standards used and will include pertinent information such as the date, analyst, compound, purity, dilution volume, etc., as appropriate.

6.2.3 Instrument Calibration

Instrument calibration protocols will meet or exceed the requirements specified in the EPA, API, or ASTM reference method employed for sample analysis. Initial instrument calibration curves will be generated, verified, and routinely monitored during instrumental analyses, as required by specific SOPs. Records of calibration, repairs, or replacement will be maintained by the designated laboratory personnel performing quality control activities and filed at the location where the work is performed.

7.0 ANALYTICAL PROCEDURES

7.1 Field Analytical and Measurement Procedures

A sample of groundwater will be collected for analysis of nephelometric turbidity, temperature, specific conductance, and pH at the well site. Equipment used to measure these parameters will be calibrated beforehand. Equipment out of calibration by 10% or more will not be used for field measurements. Laboratory measurements of specific conductance and/or pH made within 24 hours of sample collection may augment or replace field measurements, in the event of field instrument malfunction or other factors.

7.2 Laboratory Analytical and Measurement Procedures

7.2.1 List of Project Target Compounds and Laboratory Detection Limits

7.2.1.1 VOCs in groundwater

STL Houston will analyze water samples obtained from monitoring locations installed during the Vapor Intrusion Study for VOCs in accordance with USEPA SW-846 methods. Analytical procedures and project-specific laboratory reporting limits for organic compounds in water, as analyzed by USEPA SW-846 methods, are provided on Table 1.1. Laboratory reporting limits for SW-846 methods have been experimentally determined in accordance with FR vol. 49, no. 209, page 198-199.

Detection limits for the Vapor Intrusion Study will be laboratory Reporting Limits (RLs) corresponding to three to five times the method detection limit (MDL). The laboratory will report COC concentrations at or below the RLs described in this QAPP, unless the specified detection limits are not obtainable by the laboratory due to high parameter concentrations requiring sample dilution or matrix interferences. The laboratory will report COC concentrations less than the RL but greater than the MDL as estimated and will flag such results as estimated values in accordance with the laboratory data reduction procedures specified in Section 9 of this QAPP.

STL Houston has previously conducted a baseline detection limit study for all methods per USEPA CLP guidelines, and records of the study are maintained at the laboratory. Results of the study are periodically updated and/or revised when changes in instrumentation or methods occur within the laboratory. This study is intended to establish, in accordance with accepted regulatory procedures, the baseline (lowest possible) method detection limits (MDLs) and instrument detection limits (IDLs) obtainable by the laboratory. STL Houston maintains on file the results of the most recent detection limit study for project specific COCs.

Samples to be analyzed for volatile organics will be screened in the laboratory to determine what level they should be analyzed at. Samples will be analyzed either as

low or medium level concentration samples or as a series of dilutions in order to cover the expected concentration range of the site-specific compounds of interest.

7.2.1.2 VOCs in air

H&P Mobile Geochemistry will analyze air samples obtained from monitoring locations installed during the Vapor Intrusion Study for VOCs in accordance with USEPA SW-846 methods. Analytical procedures and project-specific laboratory reporting limits for organic compounds in air, as analyzed by USEPA SW-846 methods, are provided on Table 1.2. Laboratory reporting limits for SW-846 methods have been experimentally determined in accordance with EPA method TO-15.

Detection limits for the Vapor Intrusion Study will be laboratory Reporting Limits (RLs) corresponding to three to five times the method detection limit (MDL). The laboratory will report COC concentrations at or below the RLs described in this QAPP, unless the specified detection limits are not obtainable by the laboratory due to high parameter concentrations requiring sample dilution or matrix interferences. The laboratory will report COC concentrations less than the RL but greater than the MDL as estimated and will flag such results as estimated values in accordance with the laboratory data reduction procedures specified in Section 9 of this QAPP.

H&P Mobile Geochemistry has previously conducted a baseline detection limit study for all methods per USEPA CLP guidelines, and records of the study are maintained at the laboratory. Results of the study are periodically updated and/or revised when changes in instrumentation or methods occur within the laboratory. This study is intended to establish, in accordance with accepted regulatory procedures, the baseline (lowest possible) method detection limits (MDLs) and instrument detection limits (IDLs) obtainable by the laboratory. H&P Mobile Geochemistry maintains on file the results of the most recent detection limit study for project specific COCs.

During events where a mobile laboratory is employeed, samples to be analyzed for volatile organics will be screened initially by direct injection onto a GC. Samples requiring greater resolution will be collected in a Summa canister for analysis by EPA method TO-15.

A suitable lab capable of achieving required DQOs will be selected for TO-15 analyses. The selected laboratory will be required to meet the same requirements at H&P Mobile Geochemistry as outlined above and throughout the remainder of this QAPP.

7.2.1.3 Soil Physical Properties

PTS in Houston, Texas, will analyze core samples and soil samples for physical properties in accordance with laboratory SOPs prepared and reviewed for consistency with API and ASTM reference methods. Laboratory reporting limits for physical properties (see Table 1.3) have been experimentally determined in accordance with the applicable API or ASTM reference method and corresponding laboratory SOP.

GROUNDWATER SERVICES, INC.

7.2.2 List of Associated QC Samples

As summarized on Table 2.1, each laboratory SOP includes a QC section addressing minimum QC requirements for the analysis of specific analyte groups.

8.0 INTERNAL QUALITY CONTROL CHECKS

8.1 Field QC Checks

Field QC samples will be collected and analyzed in order to i) evaluate field precision and accuracy, and ii) facilitate validation of sample results. Field sampling precision and accuracy will be assessed through the collection and laboratory analysis of field replicates and field blanks. Samples will be collected per applicable procedures provided in the Field Sampling Plan.

Data from field QC samples will be examined to determine if any problems are evident for specific media or with laboratory procedures. The Contractor QA Manager will advise the Contractor Project Manager of the problems encountered so that the appropriate corrective action can be taken. Procedures for communicating corrective actions are described in Section 13 of this QAPP.

8.1.1 Blank Samples

8.1.1.1 Equipment Rinsate Blanks

Dedicated disposable sampling equipment will be used in this study, no equipment rinsate blanks are required.

8.1.1.2 Trip Blanks

The effectiveness of sample handling techniques will be evaluated by submitting preserved trip blank samples for laboratory analysis. Trip blanks will consist of a pair of 40-mL VOA vials with Teflon™ lined septa, filled in the laboratory (or organization providing the sample containers) with laboratory-grade (organic-free/de-ionized or distilled) water. The unopened trip blanks will accompany the VOC sample bottles to the sampling site and back to the laboratory in the same shipping cooler. Proper labeling and documentation will be completed for trip blanks. Trip blanks will be prepared and analyzed with other samples being analyzed for VOCs at a minimum frequency of one per day when sampling water only (i.e., no trip blanks will be required if vapor is the only medium sampled on a particular day).

8.1.2 QC Check Samples

The precision of field sample collection techniques will be evaluated by collecting and analyzing field duplicates. Duplicate samples will be defined as those samples collected simultaneously from the same source under identical conditions into separate but identical containers, and preserved, stored, transported and analyzed in the same

GROUNDWATER SERVICES, INC.

manner. Thus, to prepare a duplicate, an aliquot will be collected from a sample source and divided equally into two separate but identical sample containers. Each duplicate will be identically preserved, stored, transported and analyzed. Field duplicates will be given a different identification number to disguise the source of the sample from the laboratory. Field replicates will be analyzed by the same laboratory analyzing investigative samples.

During the course of the Vapor Intrusion Study, duplicates will be collected at a frequency of one duplicate for every 10 samples (10%) for each matrix. Field duplicates will be analyzed for VOCs only.

8.1.3 Field Instrument QC Check Samples

No field instrument QC check samples will be required.

8.2 Laboratory QC Checks

8.2.1 Analysis of Water and Vapor for COCs

STL Houston, the selected indoor air lab and H&P Mobile Geochemistry will implement a QA/QC program to ensure the reliability and validity of analyses performed in the laboratory. Analytical procedures will be documented in writing as SOPs, each including a section addressing minimum QC requirements for the procedure. Internal quality control checks differ slightly for individual procedures, but in general QC requirements will include the following:

- Method blanks
- Instrument blanks
- Matrix spikes/matrix spike duplicates
- Surrogate spikes
- Laboratory duplicates
- Laboratory control standards
- Surrogate spikes
- Internal standard spikes
- Mass spectral tuning

QC sample results will be properly recorded and included in the analytical data package. The data package will contain sufficient QC information to allow reconstruction and evaluation of the laboratory QC process by an independent data reviewer.

Data generated in the laboratory will be properly recorded and compiled into a deliverable package containing sufficient QC information for comparison to relevant criteria. Samples analyzed in non-conformance with the QC criteria will be re-analyzed by the laboratory if sufficient volume is available. The sample volumes listed on Table 3 generally provide sufficient volumes and/or weights of sample for re-analysis, if required.

Laboratory Internal Quality Control Program: Data quality objectives for internal laboratory control checks will be consistent with USEPA precision and accuracy criteria specified for selected analytical methods. STL Houston, the selected indoor air lab and H&P Mobile Geochemistry will continue to demonstrate an ability to produce acceptable results using the methods selected through the generation of acceptable QC data. Analytical data will be evaluated by STL Houston, the selected indoor air lab and H&P Mobile Geochemistry prior to submittal based on internal reviews of the QC data. Analytical quality control checks will be performed in the laboratory. These procedures will be based upon USEPA reference methods and generally accepted standards of good laboratory practice. Key components of the laboratory Analytical Quality Control Program include the following quality control practices and considerations:

- Designation of a Laboratory QA Manager to implement the laboratory QA/QC program;
- Adherence to specified laboratory sample acceptance procedures to maintain proper handling, processing, and storage of submitted samples;
- Use of the computerized laboratory data management system to record, document, and assimilate pertinent technical and administrative data;
- Use of USEPA reference methods and recommended instrumentation;
- Adherence to mandatory procedures for operation, calibration, and maintenance of laboratory and field instrumentation;
- Use of proper laboratory measuring equipment, glassware, water, chemical reagents, industrial gases;
- Constant surveillance and documentation of acceptable analytical method accuracy and precision through initial analytical method performance evaluations;
- Use of continuous surrogate spike recovery evaluations, where appropriate, to maintain acceptable method performance;
- Use of systematic method blank evaluations to identify analytical system interferences and background contamination levels;
- Adherence to proper laboratory documentation measures to maintain the complete integrity and legal validity of all laboratory analyses;
- Use of voluntary intra-laboratory performance evaluations to internally assess and evaluate analytical performance; and
- Participation in laboratory certifications, audits, and approval programs.

Analytical Data Quality: The principle criteria for validating data quality will be the continuous monitoring of acceptable analytical accuracy, precision, and overall method performance, through systematic analyses of quality control samples. STL Houston, the selected indoor air lab and H&P Mobile Geochemistry will conduct both initial and continuous analytical method performance evaluations to ensure that all generated analytical data meet applicable QC and method performance criteria. Each analytical method commonly used in the laboratory will utilize specific quality control procedures to continually monitor acceptable analytical method accuracy and precision. These specific quality control procedures are detailed in the analytical methods SOPs based upon USEPA reference methods. QC criteria for internal standards for analysis of VOCs are provided on Table 4.

GROUNDWATER SERVICES, INC.

8.2.2 Analysis of Soil Properties

PTS will implement a QA/QC program to ensure the reliability and validity of analyses performed in the laboratory. Analytical procedures will be documented in writing as SOPs, including minimum requirements for internal QC checks if any are specified by the corresponding API or ASTM reference method. QC sample results will be properly recorded and included in the analytical data package. The data package will contain sufficient QC information to allow reconstruction and evaluation of the laboratory QC process by an independent data reviewer.

Data generated in the laboratory will be properly recorded and compiled into a deliverables package containing sufficient QC information for comparison to relevant criteria. Samples analyzed in non-conformance with the QC criteria will be re-analyzed by the laboratory if sufficient volume is available.

Data quality objectives for internal laboratory control checks will be consistent with API and ASTM precision and accuracy criteria specified for selected analytical methods. PTS will continue to demonstrate an ability to produce acceptable results using the methods selected through the generation of acceptable QC data. Analytical data will be evaluated by PTS prior to submittal based on internal reviews of the QC data. Analytical quality control checks will be performed in the laboratory be based upon API and ASTM reference methods and generally accepted standards of good laboratory practice. Key components of the laboratory Analytical Quality Control Program include the following quality control practices and considerations:

- Designation of a Laboratory QA Manager to implement the laboratory QA/QC program;
- Adherence to specified laboratory sample acceptance procedures to maintain proper handling, processing, and storage of submitted samples;
- Use of the computerized laboratory data management system to record, document, and assimilate pertinent technical and administrative data;
- Use of API and ASTM analytical methods and instrumentation;
- Adherence to mandatory procedures for operation, calibration, and maintenance of instrumentation;
- Use of proper laboratory measuring equipment, glassware, water, chemical reagents, industrial gases;
- Constant surveillance and documentation of acceptable analytical method accuracy and precision through initial analytical method performance evaluations;
- Adherence to proper laboratory documentation measures to maintain the complete integrity and legal validity of all laboratory analyses;

9.0 DATA REDUCTION, VALIDATION, AND REPORTING

Data generated during field and laboratory analyses will be reduced and validated prior to reporting. No data shall be disseminated by the field crew or the laboratories until subjected to the reduction and validation procedures described below. For both field and laboratory data recording and reduction, errors will be corrected by drawing a single

line through the error, re-entering the correct information, and initialing and dating the correction.

9.1 Data Reduction

9.1.1 Field Data Reduction Procedures

Field measurements will be taken directly from field instruments which are direct reading instruments requiring no data reduction; therefore, data from these instruments will be written into field log books immediately after measurements are taken.

9.1.2 Laboratory Data Reduction Procedures

In order to convert raw data from instrument reading to reportable results, raw data will be reduced to reportable values by instrument hardware and software or by other manual procedures suggested in the applicable reference method. Reduction of laboratory measurements and laboratory reporting of analytical parameters will be conducted in accordance with the procedures specified for each USEPA, API, or ASTM analytical method. Data reduction and recordkeeping activities of the primary analyst will be as follows:

- ***General Data Reduction:*** All methods employed for analysis of samples collected during the Vapor Intrusion Study will involve certain data reduction procedures following established laboratory QA/AC protocol. The analyst will record and maintain accurate laboratory records and computer files to include sample identification, weights or volumes, dilution factors, analysis date and method, and analyst initials. Proper instrument and method calibrations will be performed and verified. The analyst will confirm results of the analytical sequence or batch, including QA/QC verification. After converting raw data to final form by following proper procedures for calculations, rounding, and significant figures, sample results will be manually transcribed or automatically transferred from the instrument report to the results data sheet. Internal chain-of-custody records will be maintained as described in Section 5 of this QAPP. The laboratory will flag analytical results in order to note the conditions listed below:
  - U = Analyte was analyzed for but not detected.
  - J = Results are estimated owing to mass spectral data indicating the presence of a compound meeting applicable identification criteria, but quantitated at less than the MQL and greater than the MDL.
  - B = Analyte detected in corresponding method or laboratory blank.
  - X = Results are flagged for a reason other than specified above as noted by the laboratory.

- ***Sample Preparation:*** Preparation analysts will record accurate data used in final calculations. Such data will be maintained in extraction and digest logbooks, bench sheets, and chemist's notebooks containing sample weights or volume, final extract volumes, surrogate and spike amounts, and standard reference numbers.

- ***Soil Properties Analyses:*** Duties of the soil properties analyst will include recording results from direct-reading or automated instruments onto a data sheet. The analyst will be responsible for transcribing, as necessary, results for selected soil properties parameters to spreadsheets for data reduction. Final results will be recorded on a data sheet and then entered into the Laboratory Information Management System (LIMS), as applicable.
- ***Instrument Analyses:*** Instrument analysts will verify calculations, analyte identifications, related QA/QC calculations, and sample results. Calculations will include surrogate spike recoveries, laboratory control sample (LCS) recoveries results of sample duplicates and matrix spikes, and results for method and matrix-specific blanks. Lab results will be recorded by the analyst on a data sheet and the associated QA/QC data sheet. Computer or integrator reduction will be employed for the analysis of volatile and semi-volatile organics by GS/MS. Instrumentation will generate a quantitation report and sample results will be calculated by computer integration, spreadsheet, or manual calculation. Positive sample results will be transcribed by the analyst to the sample results sheet and QC data entered into a QA/QC summary spreadsheet.
- ***Record Keeping:*** Bench sheets for sample extraction, digestion, and soil properties will be maintained in bound notebooks. Chromatographic documentation and data record will include sample preparation logs, extraction logs, bench sheets, instrument logs, instrument tune reports, quantitation reports, and instrument printouts. Run logs will be maintained for instrument analyses to document injection of each standard, quality control sample, and client sample. Equipment maintenance logs will be employed to document maintenance activities as discussed in Section 11 of this QAPP. Completion of chain-of-custody forms is discussed in Section 5 of this QAPP. Unused areas of the daily bench sheets and instrument logs will be crossed out, initialed and dated by the corresponding analyst or technician.

9.2 Data Validation

Data validation procedures will be performed for both field and laboratory operations as described below.

9.2.1 Procedures Used to Validate Field Data

The field data package, including field records and measurements acquired by the sampling team personnel, will be reviewed by the GSI QA Manager, as follows:

- Sampling records and chain-of-custody forms will be reviewed to verify that samples, field duplicates, and trip blanks were collected at the frequency specified in the QAPP and were properly prepared, preserved, and submitted to the laboratory.
- Instrument field records will be reviewed for documentation of proper calibration and maintenance.
- Chain-of-custody forms will be reviewed for proper completion, signatures of field personnel and the laboratory sample custodian, and dates.

GROUNDWATER SERVICES, INC.

9.2.2 Procedures Used to Validate Laboratory Data

Data production will begin with the generation of data results by the analyst and continue through a multi-level review and validation process. Each step in the review process will be performed to assure the integrity and validity of the data generated by the laboratories. Data will be sequentially passed on to the peer review analyst of the staff chemist, the department supervisor, and finally the data entry personnel. The laboratory report will be reviewed by the Laboratory QA Manager assigned to the project and then will be certified by the laboratory manager or designee. Each step in the review process will be performed to assure the integrity and validity of the date generated by the laboratories, as follows:

Quality control data (e.g., laboratory duplicates, surrogates, matrix spikes, and matrix spike duplicates) will be compared to method acceptance criteria. Data considered to be acceptable will be entered into the laboratory computer system. Data summaries will be sent to the Laboratory QA Manager for review. If approved, data will be logged into the project database. Unacceptable data will be appropriately qualified in the project report. Case narratives will be prepared to include information concerning data falling outside acceptance limits, and any other anomalous conditions encountered during sample analysis. Data will be issued after approval by the Laboratory QA Manager.

9.3 Data Reporting

9.3.1 Field Data Reporting

Field data reporting comprises a tabulation of the results of measurements made in the field (i.e., pH, conductivity, turbidity and temperature readings).

9.3.2 Laboratory Data Reporting

9.3.2.1 STL Houston, the selected indoor air lab, and H&P Mobile Geochemistry

A LIMS will be utilized for generation of laboratory data reports. After data have been entered and verified as described in Section 9.2 above, a draft report will be generated for review by the Laboratory QA Manager. Laboratory data reports will consist of sample results plus the QA/QC data specified below. The following are general requirements for each sample analyzed by the laboratory:

- The results of each analysis;
- The list of the COCs;
- The method of analysis and the detection limit for each analyte;
- Dates of sample collection, receipt, preparation, and analysis;
- Copy of the chain-of-custody forms signed by the sample custodian;
- A narrative summarizing any QA/QC non-conformances and the corrective action taken; and
- A list relating laboratory ID to sample ID.

GROUNDWATER
SERVICES, INC.

The list below describes the information to be provided for analysis of VOCs by GC/MS, as applicable:

- Evaluation of holding time, sample preservation, and percent solids;
- Dilutions;
- Results of bromofluorobenzene or decafluorotriphenylphosphine GC/MS tuning;
- Results of initial and continuing calibration;
- Results of blank analyses;
- Results of surrogates spikes, the expected value, control limits, and percent recovery;
- Results of matrix spike/matrix spike duplicate, control limits, expected value, RPD, and percent recovery;
- Results for laboratory control samples, expected value, control limits, and percent recovery;
- Results of internal standards;
- Compound identification, quantification, and detection limits; and
- Results of laboratory duplicates.

The laboratory will keep on file, for a period of three years, the following information:

- Sequential measurements readout records,
- Digestion logs,
- Percent solids raw data,
- Raw data calculation worksheets,
- GC/MS tuning and mass calculations sheets,
- Sample chromatograms,
- Mass spectra data for each sample, and
- Any other data that is associated with the samples analyzed.

After the Laboratory QA Manager has determined that the report summaries and case narratives meet project requirements, data will be compiled into a report for submittal to the GSI project manager.

9.3.2.2 PTS

After data have been entered and verified as described in Section 9.2 above, a draft report will be generated for review by the Laboratory QA Manager. Laboratory data reports will consist of sample results plus the QA/QC specified in the laboratory SOP and API or ASTM reference method.

9.4 Third-Party Data Validation

Analytical data will be validated internally by GSI and will not be submitted to a third party for independent validation. Minimum requirements will be as follows:

- Chain-of-custody documentation associated with samples.

GROUNDWATER SERVICES, INC.

- A cover sheet listing samples included in the sample data group and a cross-reference between field and laboratory sample numbers.
- A case narrative describing any analytical problems encountered during analysis of the sample data group.
- Tables summarizing analytical results with reporting limits, identification, and quantification of each parameter.
- Analytical results of quality control samples (i.e., field and laboratory blanks, initial and continuing calibration verifications, spikes, duplicates, surrogates, laboratory control samples, ICP interference check samples, chromatograms, and mass spectral data).

10.0 PERFORMANCE AND SYSTEM AUDITS

Performance and system audits will be conducted to verify that sampling and analysis are performed in accordance with applicable SOPs specified for field and laboratory activities. The audits of field and laboratory activities include two independent components: internal and external audits.

10.1 Field Performance and System Audits

10.1.1 Internal Field Audits

10.1.1.1 Internal Field Audit Responsibilities

Internal audits of field activities, including sampling and field measurements, will be conducted by the GSI Project Manager or a designated alternate. Additional team members may also be present during various phases of the audits. These audits will be conducted to evaluate performance, verify that procedures are followed, and correct deficiencies in the execution of field procedures.

10.1.1.2 Internal Field Audit Frequency

An internal field audit will be conducted at least once at the beginning of the site sample collection activities to verify that established procedures are being followed.

10.1.1.3 Internal Field Audit Procedures

To verify compliance with established procedures and implementation of appropriate QA procedures, internal audits will involve the review and examination of the following: i) field measurement and sampling records, ii) instrument operation and calibration records, iii) sample collection documentation, iv) sample handling and packaging procedures, and v) chain-of-custody procedures. Results of field performance audits will be documented on a field audit checklist. If the first audit reveals significant deficiencies, one or more follow-up audits will be conducted to verify that QA procedures are maintained throughout the Vapor Intrusion Study.

10.1.2 External Field Audits

External field audits will not be conducted during the Vapor Intrusion Study.

10.2 Laboratory Performance and System Audits

10.2.1 Internal Laboratory Audits

10.2.1.1 Internal Laboratory Audit Responsibilities

Internal system and performance audits at STL Houston, the selected indoor air lab, H&P Mobile Geochemistry and PTS will be the responsibility of the respective Laboratory QA Managers.

10.2.1.2 Internal Laboratory Audit Frequency

The internal laboratory system audit will be conducted on an annual basis, and the internal lab performance audit on a quarterly basis.

10.2.1.3 Internal Laboratory Audit Procedures

Performance and systems audits for sampling and analysis operations will include on-site review of laboratory quality assurance systems and on-site review of equipment for calibration and measurement techniques.

10.2.2 External Laboratory Audits

External laboratory audits will not be conducted as part of the Vapor Intrusion Study.

11.0 PREVENTIVE MAINTENANCE

11.1 Field Instrument Preventive Maintenance

Field instruments are to be checked and calibrated prior to beginning the field program and daily before use to verify that instruments are in good working order. Routine preventive maintenance procedures for field instruments are specified in the relevant operation manuals.

11.2 Laboratory Instrument Routine Maintenance Activities

As part of the laboratory QA/QC program, a routine preventive maintenance program will be conducted by the laboratories to minimize the occurrence of instrument failure or other system malfunction. The laboratory workload will be scheduled to accommodate planned downtime required to complete routine maintenance procedures. Trained operators will complete routine maintenance procedures (e.g., changing oven fans, replacing electronic control boards, changing vacuum pump oil, cleaning, etc.) for GC/MS instruments. An inventory of spare parts will be maintained to facilitate timely repair of instruments and minimize downtime.

GROUNDWATER SERVICES, INC.

When routine maintenance procedures do not correct a problem with instrumentation, outside repair services will be available on a next day basis. The laboratory will not maintain test equipment to be used in the maintenance of instrumentation; rather, service representatives will bring the necessary test equipment for the service call.

Records of preventive maintenance activities for each piece of equipment will be maintained in Calibration and Maintenance log books assigned to that instrument. Preventive maintenance performed during the project will be noted in the field logbook and the instrument Calibration and Maintenance log book.

11.3 Inspection/Acceptance Requirements for Supplies and Consumables

Supplies and spare parts will be maintained for both field and laboratory instruments to assure timely completion of sample screening and analysis. For field work, critical spare parts such as batteries will be kept on-site to reduce downtime. Backup instruments and equipment will be available on-site or within 1 day shipment to avoid delays in the field schedule. An inventory of spare parts will also be kept on hand in order to complete the routine maintenance tasks described in Section 11.2.

12.0 PROCEDURES TO ASSESS DATA QUALITY OBJECTIVES

12.1 Accuracy Assessment

In order to evaluate the accuracy of laboratory results, LCSs and MS/MSDs will be prepared at the frequency shown on Table 2.4 by spiking with VOCs prior to analysis. For the LCS, the ratio between the measured concentration and the known concentration in the spiked sample converted to a percentage is equal to the percent recovery. For MS/MSDs, the difference between the measured concentration in the spike and the concentration in the native sample is divided by the known spike concentration to obtain the percent recovery, as follows:

$$\%R = \frac{\textit{Measured Concentration in Spike Sample} - \textit{Concentration in Native Sample}}{\textit{Known Spike Concentration}} \times 100$$

Daily tabulations for each commonly analyzed organic compound will be maintained on instrument-specific, matrix-specific, and analyte-specific bases. Control charts of results obtained from LCS will be maintained for selected organic analytes to track the accuracy of laboratory data

12.2 Precision Assessment

Spiked samples will be prepared by selecting a sample at random from each sample shipment received at the laboratory, dividing the sample into equal aliquots, and then spiking each of the aliquots with a known amount of analyte. The duplicate samples will then be included in the analytical sample set. The splitting of the sample allows the

GROUNDWATER SERVICES, INC.

analyst to determine the precision of the preparation and analytical techniques associated with the duplicate sample. The RPD between the spike and duplicate spike (or between MS and MSD) will be calculated as follows:

$$RPD = \frac{Concentration\ in\ Spike\ 1 - Concentration\ in\ Spike\ 2}{0.5(Concentration\ in\ Spike\ 1 + Concentration\ in\ Spike\ 2)} \times 100$$

12.3 Completeness Assessment

Completeness is the ratio of the number of valid sample results to the total number of samples analyzed with a specific matrix and/or analysis. After analytical testing, the percent completeness will be calculated as follows

$$Completeness = \frac{(number\ of\ valid\ measurements)}{(number\ of\ measurements\ planned)} \times 100$$

13.0 CORRECTIVE ACTION

Corrective action will be taken to identify, recommend, approve, and implement measures to remedy unacceptable procedures or out-of-control performances potentially affecting data quality. Corrective actions may be required for i) non-conformance with procedures specified by the QAPP, ii) malfunction of sampling or analytical equipment, or iii) changes in sampling network or frequency. Non-conformances include those instances of conducting activities outside the requirements of the QAPP (i.e., missing holding times or detecting blank contamination). Analytical and equipment problems may occur during sampling, sample handling, sample preparation, or laboratory analysis. Modifications in the sampling network may result from inaccessible locations or from inadvertent omissions in sample collection.

Any non-conformance to quality control procedures specified in the QAPP will be identified, reported, and corrected. If the non-conformance is identified during sample collection or analysis, corrective action will be implemented immediately by the field technician or laboratory analyst. If the non-conformance is identified during an internal/external audit or third-party data validation, corrective action will be implemented after notification of the GSI Project Manager, and/or the Laboratory Project Manager. Any corrective actions taken during the course of the Vapor Intrusion Study will be documented in the final project report described in Section 14 of this QAPP.

13.1 Field Corrective Action

13.1.1 Corrective Action for Procedural Non-Conformances

The GSI Field Operations Manager and Field Technical Staff will be responsible for reporting suspected technical or QA non-conformances or deficiencies to the GSI Project Manager. The GSI Project Manager will be responsible for ensuring that any

GROUNDWATER SERVICES, INC.

necessary corrective actions are implemented. If appropriate, the GSI Project Manager will suspend additional work depending on the nature of the non-conforming activity until the corrective action is completed. The GSI Project Manager will ensure that corrective action for the non-conformance is completed by evaluating and controlling additional work on non-conforming items, determining appropriate action, and communicating with concerned persons via telephone, e-mail, or other medium.

13.1.2 Corrective Action for Changes in Sampling Network

The Contractor Field Operations Manager will communicate work plan modifications to project management for review and approval prior to implementation of significant modifications to the QAPP. In order to avoid unnecessary project delays, minor field adjustments (e.g., moving a sampling location less than 25 ft to avoid an obstruction) will be made at the discretion of the GSI Field Operations Manager and implemented without prior approval from project management, provided other health and safety considerations have been addressed (e.g., utility clearance). Such modifications will be recorded in the field logbook and brought to the prompt attention of project management. The GSI Project Manager will then review the modification to ensure that the modification does not compromise project quality assurance objectives. GSI Field Technical Staff will not initiate work program modifications without prior communication with the GSI Field Operations Manager.

Significant plan modifications will be implemented only after obtaining the approval of the GSI Project Manager. Program changes will be documented and copies of the affected document will be distributed to recipients via e-mail or other medium. The GSI Project Manager will be responsible for the controlling, tracking, and implementation of the identified changes. A discussion of field program modifications will be included in the final project report.

If the proposed modification has the potential to adversely impact attainment of project QA objectives, the GSI Project Manager will be notified while the sampling crew is still in the field. Such a situation would result if i) a sampling location were to be eliminated; ii) a sampling location were to be moved a significant distance from its designated location owing to access limitations or obstructions; or iii) sampling frequency were to be decreased. Possible corrective actions could include i) re-mobilization to collect additional samples, or ii) evaluation to determine if data already collected were sufficient to satisfy QA objectives.

If the GSI Project Manager determine that the modification will not adversely impact the achievement of project QA objectives, no further action will be taken and a summary of the findings will be included in the final project report. If the modification has the potential to adversely impact the achievement of project QA objectives, additional locations will be sampled or additional samples will be collected and the findings documented in the final project report.

GROUNDWATER SERVICES, INC.

13.1.3 Field Corrective Action Reports

In all cases in which corrective actions of field procedures are required, a description of the nature of the problem, an evaluation of the cause, if known, and the action taken will be prepared by the GSI Field Operations Manager or QA Manager and distributed by e-mail, U.S. mail, or other appropriate medium. The following topics will be discussed:

- Where did the out-of-control event occur (site, location, etc.)?
- When did the incident occur and when was it corrected?
- What was the nature of the out-of-control event?
- Who discovered the out-of-control incident, verified the incident, and corrected the problem?
- What was the method number and name of the test?
- What was the disposition of the test or control and/or instrument?
- What was the nature of the corrective action?
- What will be done to prevent the reoccurrence of the problem?
- Why did the incident happen (if scientific explanation is available)?

A copy of the subject control data and other information describing the non-compliant condition will be included in the final project report. Deficiencies identified during the data validation and assessment process will also be included in the final project report.

13.2 Laboratory Corrective Action

Data packages prepared by the laboratory will include a discussion of the QC problems encountered and corrective actions taken. If an out-of-control event or potential out-of-control event is noted in the laboratory, an investigation and corrective action will be taken appropriate to the analysis and the event. Laboratory corrective action may be required if any of the following occur:

- QC data are outside the warning or acceptable windows for precision and accuracy,
- Blanks contain target analytes above acceptable levels,
- Undesirable trends are detected in spike recoveries or RPDs between duplicates,
- Unusual changes in detection limits are noted,
- Deficiencies are detected by the QA Department during internal or external audits or from the results of performance evaluation samples, or
- Inquiries concerning data quality are received.

The Laboratory QA Manager will be responsible for implementing laboratory corrective action. Individual analysts will be responsible for assessing the results from sample analysis. Results not meeting applicable criteria will be reported to a supervisor who will recommend a corrective action to be implemented by the section manager, the QC chemist and the QA/QC Supervisor. The Laboratory QA Manager will be responsible for ensuring that corrective actions are taken, as appropriate, in the following situations:

GROUNDWATER SERVICES, INC.

- ***Out-of-Control Criteria:*** An out-of-control situation will exist when a blank, calibration standard, laboratory control sample, sample replicate, or spike recovery analysis fails to meet applicable quality control criteria. Corrective action procedures are often handled at the bench level by the analyst who reviews the preparation for possible errors, checks the instrument calibration, spike and calibration mixes, and instrument sensitivity. If the out-of-control situation cannot be remedied by the analyst, an investigation to determine the cause of the problem will be undertaken by the analyst and department supervisor, and a Quality Assurance Action Report will be initiated. Analyses completed during the out-of-control situation will be repeated after the out-of-control situation has been corrected. If the problem persists or cannot be identified, the matter will be referred to the laboratory supervisor, manager and/or QA Department for further investigation. After resolution, the corrective action procedure will be documented and filed with the QA Department.
- ***Warning Criteria:*** Corrective measures will be implemented when one of the following two conditions occurs: i) quality assurance data for blanks, laboratory control samples, sample replicates, or matrix spikes exceed two standard deviations of applicable limits or ii) a trend or shift is observed for the reference standard. Provided other criteria are within applicable limits, samples need not be re-analyzed. A Quality Assurance Corrective Action Report will be initiated by the analyst and the Laboratory Supervisor, and corrective action will be implemented prior to analyzing additional samples. If the situation occurs with the next sample batch, an out-of-control situation exists, and steps outlined above are taken. If matrix interference is indicated by out-of-control replicate analyses or matrix spike recovery data, re-analysis of a sample batch is necessary only when other QC data do not meet applicable specifications.
- ***Performance Audit:*** If the laboratory fails to meet applicable requirements reviewed during a performance of systems audit, corrective action will be taken. The QA/QC coordinator will notify the Laboratory Project Manager and the USEPA QA Manager in the event of a corrective action taken in response to an audit. Applicable federal and state guidelines and requirements regarding response to audit findings are observed by laboratory.

13.3 Corrective Action During Data Validation and Data Assessment

The GSI QA Manager will review analytical reports generated by STL Houston, the selected indoor air lab, H&P Mobile Geochemistry and PTS prior to data use and filing. Upon receiving data validation or data assessment results, the GSI QA Manager will identify the need for corrective action and notify concerned persons by telephone, e-mail, or other appropriate medium. Specified corrective action will be developed to assure meeting required QA objectives. The GSI Project Manager and the Laboratory Project Managers will be responsible for implementing corrective actions in the field and laboratory, respectively. Corrective action required may include re-sampling, collecting additional samples, or re-measurement of field parameters. The laboratory may be required to repair or re-calibrate instrumentation, re-inject or re-analyze samples, or

GROUNDWATER SERVICES, INC.

provide additional raw data. Proposed and implemented corrective actions will be documented in the final project.

14.0 QUALITY ASSURANCE REPORTS TO MANAGEMENT

The final report for the Vapor Intrusion Study will be the responsibility of the GSI Project Manager. The final report will contain a section identified as the Project QA Report that addresses data quality, including the accuracy, precision, and completeness of the data, results of any performance or system audits, and any corrective action needed or taken during the project.

14.1 Contents of Project QA Report

The QA report will contain i) results of field and laboratory audits conducted during the time period covered by the report, ii) an assessment of QA results with respect to data quality objectives, iii) a summary of corrective actions that may have been implemented, and iv) results of any corrective action activities. If applicable, references to QAPP modifications will be highlighted.

14.2 Frequency of QA Reports

The Project QA Report will be prepared on a one-time basis and submitted in conjunction with the final report for the Vapor Intrusion Study.

15.0 REFERENCES

USEPA, 1994a. *Guidance for the Data Quality Objectives Process*, U. S. Environmental Protection Agency.

USEPA, 1994b. *National Functional Guidelines for Organic Data Review*, U.S. Environmental Protection Agency, December 1994.

USEPA, 1998. *Region 5 RCRA QAPP Instructions,* U. S. Environmental Protection Agency. Revision: April1998.

GROUNDWATER SERVICES, INC.

TABLE 1.1
ANALYTICAL PARAMETERS AND DATA QUALITY OBJECTIVES FOR WATER

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

Analyte	CAS Number	Analytical Method Prep.	Analytical Method Det.	MDL mg/L	RL mg/L	Investigation DQO mg/L
Volatile Organics						
Acetone	67-64-1	5030B	8260B	5.00E-03	2.50E-02	2.50E-02
Benzene	71-43-2	5030B	8260B	3.60E-04	1.00E-03	1.00E-03
Bromodichloromethane	75-27-4	5030B	8260B	1.40E-04	1.00E-03	1.00E-03
Bromoform	75-25-2	5030B	8260B	3.30E-04	1.00E-03	1.00E-03
Bromomethane	74-83-9	5030B	8260B	6.20E-04	1.00E-03	1.00E-03
Carbon disulfide	75-15-0	5030B	8260B	6.60E-04	1.00E-03	1.00E-03
Carbon tetrachloride	56-23-5	5030B	8260B	3.10E-04	1.00E-03	1.00E-03
Chlorobenzene	108-90-7	5030B	8260B	3.40E-04	1.00E-03	1.00E-03
Chloroethane	75-00-3	5030B	8260B	7.80E-04	1.00E-03	1.00E-03
Chloroform	67-66-3	5030B	8260B	3.70E-04	1.00E-03	1.00E-03
Chloromethane	74-87-3	5030B	8260B	3.90E-04	1.00E-03	1.00E-03
Dibromochloromethane	124-48-1	5030B	8260B	5.00E-04	1.00E-03	1.00E-03
Dichloroethane, 1,1-	75-34-3	5030B	8260B	3.60E-04	1.00E-03	1.00E-03
Dichloroethane, 1,2-	107-06-2	5030B	8260B	2.60E-04	1.00E-03	1.00E-03
Dichloroethene, 1,1-	75-35-4	5030B	8260B	3.60E-04	1.00E-03	1.00E-03
Dichloroethene, cis-1,2-	156-59-2	5030B	8260B	3.80E-04	1.00E-03	1.00E-03
Dichloroethene, trans-1,2-	156-60-5	5030B	8260B	4.00E-04	1.00E-03	1.00E-03
Dichloropropane, 1,2-	78-87-5	5030B	8260B	3.30E-04	1.00E-03	1.00E-03
Dichloropropene, cis-1,3-	10061-01-5	5030B	8260B	2.30E-04	1.00E-03	1.00E-03
Dichloropropene, trans-1,3-	10061-02-6	5030B	8260B	2.60E-04	1.00E-03	1.00E-03
Ethylbenzene	100-41-4	5030B	8260B	3.40E-04	1.00E-03	1.00E-03
Hexanone, 2-	591-78-6	5030B	8260B	9.30E-04	1.00E-02	1.00E-02
Methyl Ethyl Ketone (Butanone, -2)	78-93-3	5030B	8260B	1.30E-03	1.00E-02	1.00E-02
Methyl-2-pentanone, 4-	108-10-1	5030B	8260B	6.50E-04	1.00E-02	1.00E-02
Methylene chloride	75-09-2	5030B	8260B	6.40E-04	5.00E-03	5.00E-03
Styrene	100-42-5	5030B	8260B	2.50E-04	1.00E-03	1.00E-03
Tetrachloroethane, 1,1,2,2-	79-34-5	5030B	8260B	1.80E-04	1.00E-03	1.00E-03
Tetrachloroethene	127-18-4	5030B	8260B	3.50E-04	1.00E-03	1.00E-03
Toluene	108-88-3	5030B	8260B	5.40E-04	1.00E-03	1.00E-03
Trichloroethane, 1,1,1-	71-55-6	5030B	8260B	3.20E-04	1.00E-03	1.00E-03
Trichloroethane, 1,1,2-	79-00-5	5030B	8260B	2.20E-04	1.00E-03	1.00E-03
Trichloroethene	79-01-6	5030B	8260B	3.70E-04	1.00E-03	1.00E-03
Vinyl chloride	75-01-4	5030B	8260B	5.60E-04	1.00E-03	1.00E-03
Xylenes (total)	1330-20-7	5030B	8260B	1.30E-03	2.00E-03	2.00E-03

Notes:
- # Investigation DQOs correspond to the reporting limit (RL) for each analyte.
- # Method detection limits (MDLs) and reporting limits (RLs) shown are based on data provided by STL Savannah. Analytical methods are referenced from "Test Methods for Evaluating Solid Wastes, SW-846, Update III, 3rd edition," December 1996.
- # Applicable results will be reported as estimated value between method detection limit (MDL) and the reporting limit (RL).
- # Laboratory MDLs are continuously being evaluated and may differ slightly from these values.
- # Prep. = Digestion or extraction method.
  Det. = Determinative method for quantitation.

— = No value specified.
NA = Not applicable to this constituent.

GROUNDWATER SERVICES, INC.

TABLE 1.2
ANALYTICAL PARAMETERS AND LABORATORY REPORTING LIMITS FOR VAPOR

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

Analyte	Analytical Method / CAS Number	8260 Mobile Lab RL ug/m3	8260 SIM Mobile Lab RL ug/m3	TO-15 H&P RL ug/m3	TO-15 SIM Columbia MDL ug/m3	TO-15 SIM Columbia RL ug/m3
Volatile Organics						
Benzene	71-43-2	NA	NA	3	0.027	0.1
Bromomethane	74-83-9	NA	NA	4	NA	NA
Carbon tetrachloride	56-23-5	NA	NA	6	0.0016	0.025
Chlorobenzene	108-90-7	NA	NA	5	0.0025	0.025
Chloroethane	75-00-3	NA	NA	3	0.0026	0.025
Chloroform	67-66-3	NA	NA	5	0.024	0.1
Chloromethane	74-87-3	NA	NA	2	0.0038	0.025
Dichloroethane, 1,1-	75-34-3	NA	NA	4	0.0027	0.025
Dichloroethane, 1,2-	107-06-2	NA	NA	4	0.0023	0.025
Dichloroethene, 1,1-	75-35-4	NA	NA	4	0.0025	0.025
Dichloroethene, cis-1,2-	156-59-2	1000	5	4	0.0031	0.025
Dichloroethene, trans-1,2-	156-60-5	1000	5	4	0.0029	0.025
Dichloropropane, 1,2-	78-87-5	NA	NA	5	0.0025	0.025
Dichloropropene, cis-1,3-	10061-01-5	NA	NA	5	0.0019	0.025
Dichloropropene, trans-1,3-	10061-02-6	NA	NA	5	NA	NA
Ethylbenzene	100-41-4	NA	NA	4	0.0025	0.025
Methylene chloride	75-09-2	NA	NA	3	0.029	0.1
Styrene	100-42-5	NA	NA	4	NA	NA
Tetrachloroethane, 1,1,2,2-	79-34-5	NA	NA	7	0.0029	0.025
Tetrachloroethene	127-18-4	1000	5	7	0.0024	0.025
Toluene	108-88-3	NA	NA	7	0.027	0.1
Trichloroethane, 1,1,1-	71-55-6	NA	NA	5	0.0025	0.025
Trichloroethane, 1,1,2-	79-00-5	NA	NA	5	0.0027	0.025
Trichloroethene	79-01-6	1000	5	5	0.0025	0.025
Vinyl chloride	75-01-4	1000	5	3	0.0027	0.025
Xylenes (total)	1330-20-7	NA	NA	4	NA	NA

Notes:
1. Table summarizes proposed analytical methods and data quality objectives (DQOs).
2. Investigation DQOs correspond to 2 times the achievable detection level (MDL) or the reporting limit (RL) for each analyte.
3. Method detection limits (MDLs) and reporting limits (RLs) shown are based on data provided by selected analytical laboratories.
4. Applicable results may be reported as an estimated value between method detection limit (MDL) and the reporting limit (RL).
5. Laboratory MDLs are continuously being evaluated and may differ slightly from these values.
6. Mobile lab = H&P Mobile Geochemistry, H&P = H&P fixed laboratory, Columbia = Columbia Analytical Services, Inc..
7. Prep. = Digestion or extraction method.
   Det. = Determinative method for quantitation.
   DQO = Data quality objective
   NA = Not available

GROUNDWATER
SERVICES, INC.

TABLE 1.3
ANALYTICAL PARAMETERS FOR SOIL CORES

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

Analysis	Analytical Method
Physical Properties	
Intrinsic Permeability	API RP 40 / ASTM D2434
Porosity, total and air-filled	API RP 40
Dry Bulk Density	API RP 40/ASTM D4564/ASTM D2937
Volumetric Moisture Content	ASTM DD216/ASTM D4959/ ASTM D4643
Fraction Organic Carbon	Walkley-Black, EPA 9060

Notes:
1. Physical properties analysis will be performed by PTS Geolabs, Houston, Texas, in accordance with ASTM and API standards.

GROUNDWATER SERVICES, INC.

TABLE 1.4
ANALYTICAL PARAMETERS AND DATA QUALITY OBJECTIVES FOR RADON ANALYSIS

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

Analysis	Analytical Method	Detection Limit	Investigation DQO
		pCi/L	pCi/L
Radon			
Activated Carbon	USEPA #402-R-93-004 079	0.4	0.4
Radon Gas Analysis	Mathieu, 1998	0.4	0.4
Radon Gas Extraction	Berelson, 1987	NA	NA

Notes:
1. Activated carbon analysis will be performed by Accustar Labs, Medway, Massachussetts.
2. Radon gas analysis will be performed by Doug Hammond, University of Southern California.
3. NA = Not applicable to this analysis.

GROUNDWATER SERVICES, INC.

TABLE 2.1
PRECISION AND ACCURACY OBJECTIVES FOR LABORATORY QC SAMPLES

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes

Parameter	EPA Reference Method	QC Sample Type	Frequency	Data Quality Objectives: Precision (% RPD) Aqueous	Precision (% RPD) Air	Precision (% RPD) Soil Core	Accuracy Aqueous	Accuracy Air	Accuracy Soil Core
1. Volatile Organics	Water: 8260B Air: GC/TO-15	Method Blank	1 per 12 hr of analysis	NA	NA	NA	Target Analytes <RL	Target Analytes <RL	NA
		Laboratory Spike and Duplicate	1 per 20 samples	See Table 2.2	<35	NA	See Table 2.2	65-135%	NA
		Matrix Spike and Duplicate	1 per 20 samples	See Table 2.2	NA	NA	See Table 2.2	NA	NA
2. Intrinsic Permeability	API RP 40 / ASTM D2434	Lab Control Standard	NA	NA	NA	NA	NA	NA	NA
3. Porosity	API RP 40	Lab Control Standard	NA	NA	NA	NA	NA	NA	+0.02% Pore Volume
4. Bulk Density	API RP 40/ASTM D4564 ASTM D2937	Lab Control Standard	NA	NA	NA	NA	NA	NA	+0.5 of 1 Porosity %
5. Volumetric Moisture Content	ASTM DD216/ASTM D4959 ASTM D4643	Lab Control Standard	NA	NA	NA	NA	NA	NA	NA
6. Fraction Organic Carbon	Walkley-Black, EPA 9060	Method Blank	NA	NA	NA	NA	NA	NA	+3.0% Method Response Factor
		Lab Control Standard and Duplicate	NA	NA	NA	)% Initial Va	NA	NA	+30% Certified Value

Notes:
1. Precision objectives represent relative percent difference (% RPD) between duplicates.
2. Samples, standards, and quality control (QC) samples analyzed for volatile organics will be spiked with surrogates (see Table 2.3).
3. NA = Precision/accuracy data quality objective not applicable to this QC sample.
   RL = Reporting limit.
   RPD = Relative percent difference
   %R = Percent recovery

GROUNDWATER SERVICES, INC.

TABLE 2.2
PRECISION AND ACCURACY OBJECTIVES FOR CONSTITUENTS

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes:
Altus AFB Site

Analyte	CAS Number	Analytical Method Prep.	Analytical Method Det	Accuracy (%Rec)	Precision (% RPD)
Volatile Organics					
Acetone	67-64-1	5030B	8260B	32-164	≤ 50
Benzene (MS)	71-43-2	5030B	8260B	69-128	≤ 30
Bromodichloromethane	75-27-4	5030B	8260B	69-134	≤ 30
Bromoform	75-25-2	5030B	8260B	69-138	≤ 30
Bromomethane	74-83-9	5030B	8260B	22-184	≤ 50
Carbon disulfide	75-15-0	5030B	8260B	55-140	≤ 30
Carbon tetrachloride (MS)	56-23-5	5030B	8260B	67-136	≤ 30
Chlorobenzene (MS)	108-90-7	5030B	8260B	72-126	≤ 30
Chloroethane	75-00-3	5030B	8260B	40-158	≤ 50
Chloroform	67-66-3	5030B	8260B	72-124	≤ 30
Chloromethane	74-87-3	5030B	8260B	40-123	≤ 50
Dibromochloromethane	124-48-1	5030B	8260B	72-132	≤ 30
Dichloroethane, 1,1-	75-34-3	5030B	8260B	41-158	≤ 30
Dichloroethane, 1,2-	107-06-2	5030B	8260B	61-143	≤ 30
Dichloroethene, 1,1- (MS)	75-35-4	5030B	8260B	53-144	≤ 30
Dichloroethene, cis-1,2-	156-59-2	5030B	8260B	57-132	≤ 30
Dichloroethene, trans-1,2-	156-60-6	5030B	8260B	48-149	≤ 30
Dichloropropane, 1,2-	78-87-5	5030B	8260B	74-122	≤ 30
Dichloropropene, cis-1,3-	10061-01-5	5030B	8260B	77-127	≤ 30
Dichloropropene, trans-1,3-	10061-02-6	5030B	8260B	73-133	≤ 30
Ethylbenzene	100-41-4	5030B	8260B	76-120	≤ 30
Hexanone, 2-	591-78-6	5030B	8260B	43-158	≤ 30
Methyl ethyl ketone (MEK, 2-Butanone)	78-93-3	5030B	8260B	38-153	≤ 30
Methyl-2-pentanone, 4- (MIBK)	108-10-1	5030B	8260B	46-156	≤ 30
Methylene chloride	75-09-2	5030B	8260B	63-133	≤ 50
Styrene	100-42-5	5030B	8260B	75-123	≤ 30
Tetrachloroethane, 1,1,2,2-	79-34-5	5030B	8260B	61-139	≤ 30
Tetrachloroethene	127-18-4	5030B	8260B	71-129	≤ 30
Toluene (MS)	108-88-3	5030B	8260B	71-129	≤ 30
Trichloroethane, 1,1,1-	71-55-6	5030B	8260B	68-135	≤ 30
Trichloroethane, 1,1,2-	79-00-5	5030B	8260B	70-129	≤ 30
Trichloroethene (MS)	79-01-6	5030B	8260B	70-123	≤ 30
Vinyl chloride	75-01-4	5030B	8260B	50-142	≤ 50
Xylenes (total)	1330-20-7	5030B	8260B	77-121	≤ 30

Notes:
1. Laboratory control limits based upon data provided by STL Savannah.
2. %Rec = Percent recovery. %RPD = Relative percent difference.
   a = Information is pending.

GROUNDWATER SERVICES, INC.

TABLE 2.3
LABORATORY CONTROL LIMITS FOR SURROGATES IN ANALYTICAL CONSTITUENTS

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes: Altus AFB Site

Analyte	EPA SW-846 Reference Method	Laboratory Control Limits for Percent Recovery	
		Water (%)	Air (%)
Volatile Organics			
p-Bromofluorobenzene	8260B/TO-15	70-119	80-120
Dibromofluoromethane	8260B/TO-15	68-129	80-120
Toluene-d8	8260B/TO-15	74-122	80-120

Notes:
1. Control limits based upon historical data provided by STL Savannah and EPA values published in method TO-15.
2. Laboratory procedures will be conducted in accordance with the EPA reference methods shown above.

GROUNDWATER SERVICES, INC.

TABLE 2.4
REQUIREMENTS FOR FIELD QUALITY ASSURANCE SAMPLES

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes: ESTCP Vapor Intrusion Study

QA Sample Type	Matrix	Laboratory Analytes	Preparation/Collection Method	Frequency	Data Quality Objectives
Field Duplicates	*Water*	Volatile Organics	Collect an additional set of 3-40 ml glass vials	1 per 10 samples	±30% RPD between duplicates
	Air	Volatile Organics	Collect an additional air sample	1 per 10 samples	±30% RPD between duplicates
	Air	Radon	Collect an additional air sample	1 per 10 samples	±30% RPD or 0.5 pCi/L, whichever is larger, difference between duplicates
Matrix Spike and Duplicates	*Water*	Volatile Organics	Collect 2 additional sets of 3-40 ml glass vials	1 per 20 samples	See Table 3.2
	Air	Volatile Organics	NA	NA	NA
Field Blanks	*Water*	Volatile Organics	3-40 mL glass vials filled with distilled water under field conditionds	1 per day when soil or water is being sampled	Target Parameter Concentrations <RL
	Air	Volatile Organics	Summa Canister or Syringe	1 per sampling event	
Trip Blanks	*Water*	Volatile Organics	3-40 mL glass vials filled with distilled water in laboratory prior to sampling	1 per shipping container	Target Parameter Concentrations <RL
	Air	Volatile Organics	Summa Canister	1 per mobilization	Concentrations <RL
Background	*Air*	Radon	Collect ambient air sample	1 per sampling location	NA

Notes:
1. RL = Reporting limit. NA = Not applicable.

GROUNDWATER SERVICES, INC.

TABLE 3
SAMPLE CONTAINER, PRESERVATION, AND HOLDING TIME REQUIREMENTS

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes: Altus AFB Site

Parameter Group	Reference Method	Sample Container and Preservative	Sample Storage	Maximum Holding Time: Extraction or Derivatization	Maximum Holding Time: Analysis after Extraction or Derivatization
Volatile Organics					
Water	8260	3 - 40 mL glass vials, HCl to pH<2, headspace free	4±2° C	NA	14 days
Air	GC/TO-15	Gas tight syringe/Summa canister	NA		14 days
Physical Properties (Soils)					
Intrinsic Permeability	API RP 40 / ASTM D2434	2" X 6" tube per sample, chill	4±2° C	NA	NA
Porosity, total and air-filled	API RP 40	2" X 6" tube per sample, chill	4±2° C	NA	NA
Dry Bulk Density	API RP 40/ASTM D4564/ASTM D2937	2" X 6" tube per sample, chill	4±2° C	NA	NA
Volumetric Moisture Content	ASTM DD216/ASTM D4959/ ASTM D4643	100 grams, chill	4±2° C	NA	NA
Fraction Organic Carbon	Walkley-Black, EPA 9060	100 grams, 4° required	4±2° C	NA	NA
Radon					
Air	Mathieu and Berelson	Evacuated glass cylinder and Tedlar bag	NA	As soon as possible	As soon as possible

Notes:
1. Laboratory procedures will be conducted in accordance with the reference methods specified above.
2. Core samples sent to PTS labs will be shipped on dry ice.
   NA = Not applicable to this analysis or matrix.
3. Radon samples will be shipped for analysis immediately after sampling.

GROUNDWATER SERVICES, INC.

TABLE 4
LABORATORY CONTROL LIMITS FOR INTERNAL STANDARDS: VOLATILE ORGANICS

QAPP for Demonstration Plan for Detailed Field Investigation of Vapor Intrusion Processes:
Altus AFB Site

Parameter	EPA SW-846 Reference Method	Laboratory Control Limits Relative to Calibration Standard	
		Peak Area Counts	Retention Time
Volatile Organics			
Bromochloromethane	TO-15	NA	+/- 0.5 minutes
1,4-Difluorobenzene	TO-15	NA	+/- 0.5 minutes
Chlorobenzene-d5	TO-15	NA	+/- 0.5 minutes

Notes:
1. Control limits based upon data provided by STL and EPA published limits
2. Laboratory procedures will be conducted in accordance with the EPA reference methods shown above.

Environmental Security Technology Certification Program
(ESTCP)

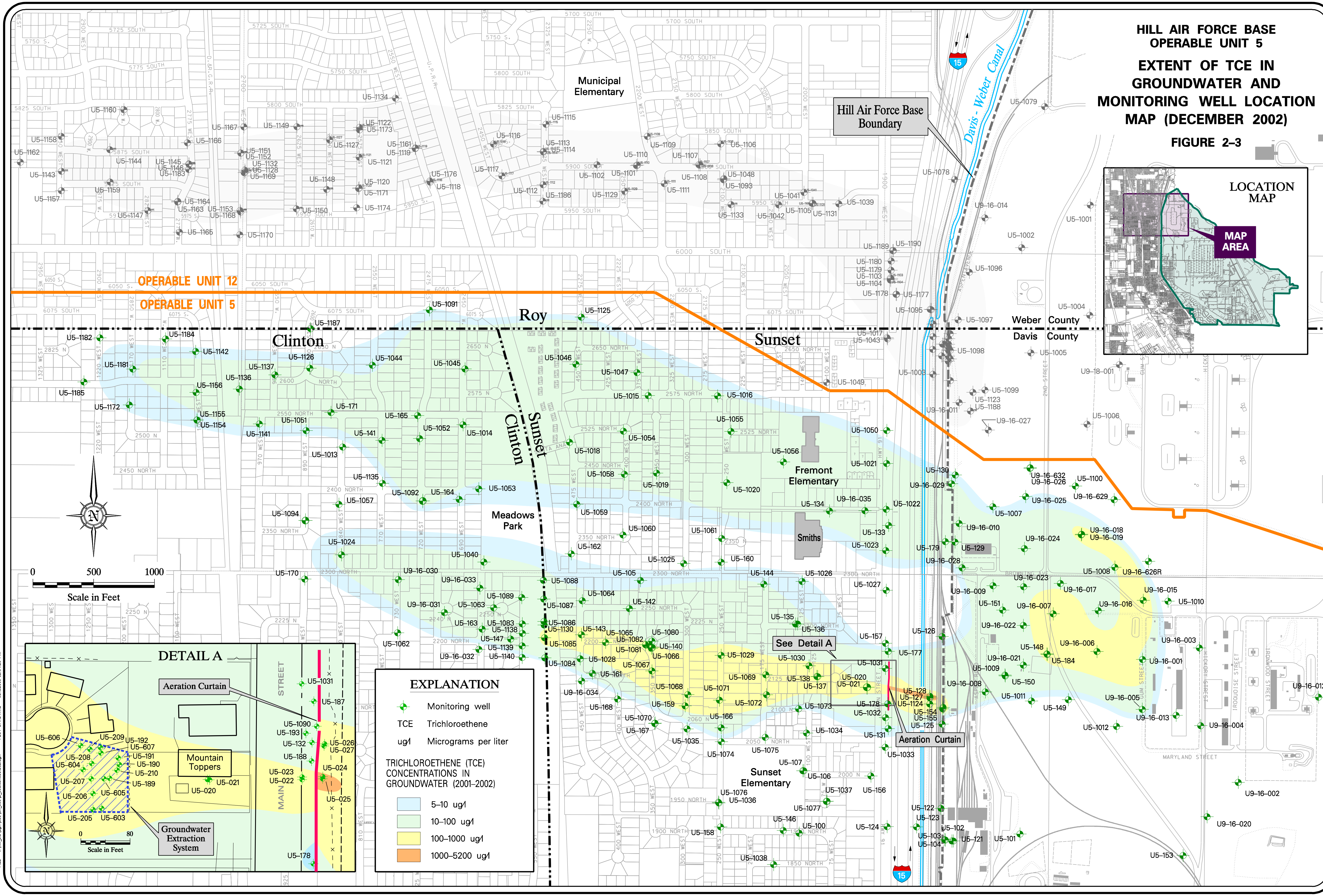
DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix C

Supplemental Figures for Hill AFB and Altus AFB

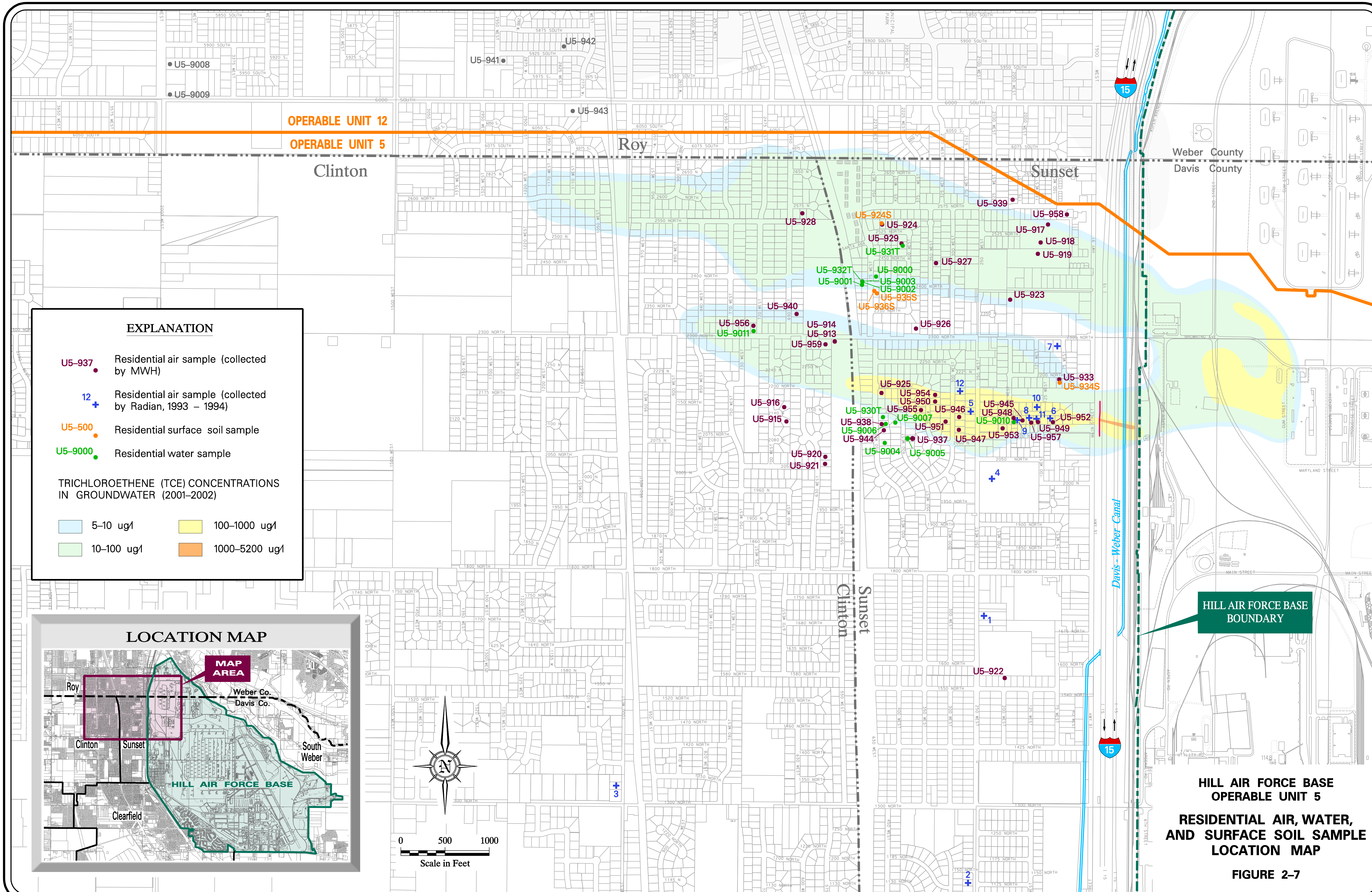
Hill AFB RI Figures

Altus AFB RFI Figures



EXTENT OF TCE IN GROUNDWATER AND MONITORING WELL LOCATION MAP (DECEMBER 2002)

FIGURE 2–3



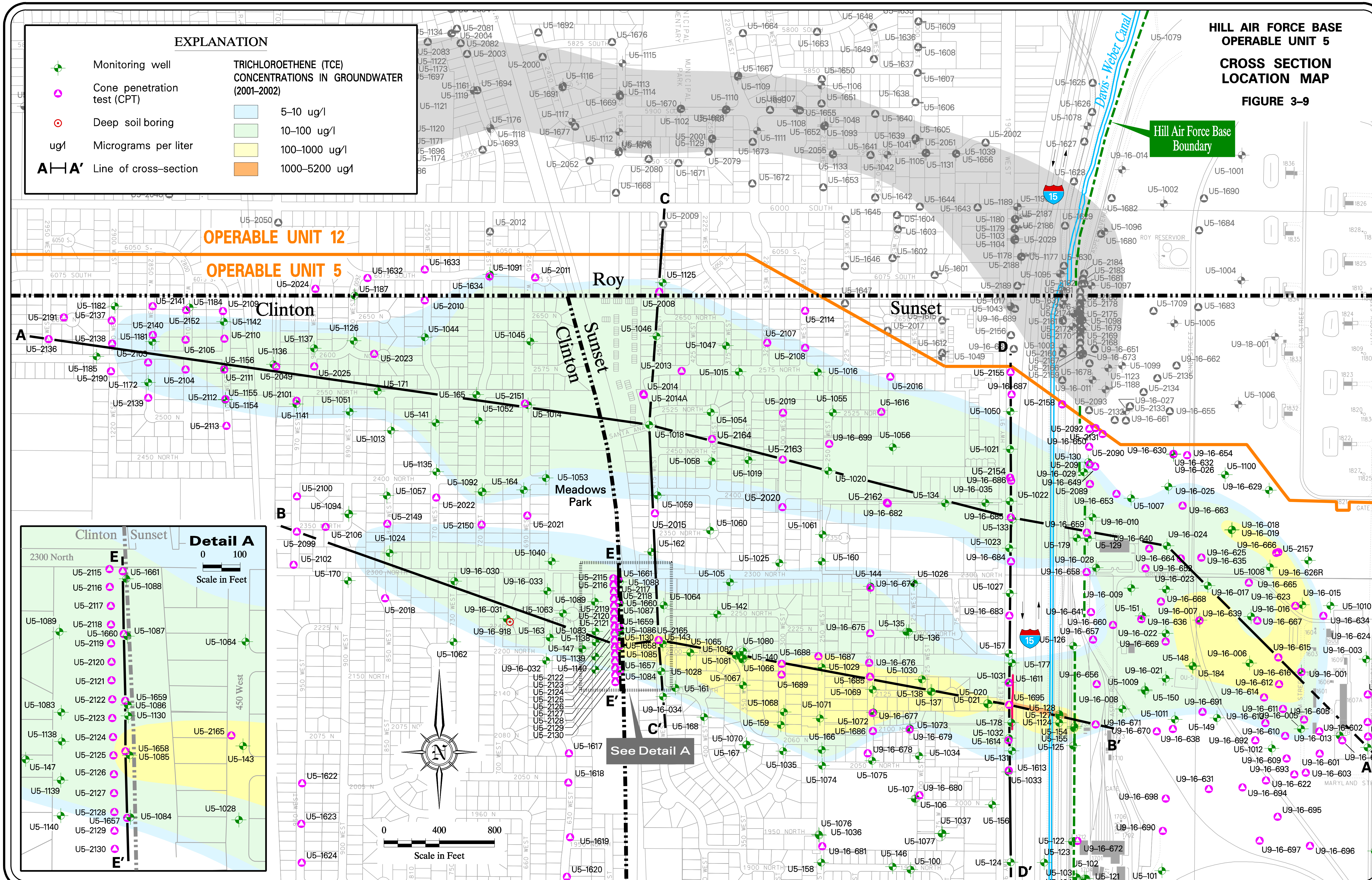
HILL AIR FORCE BASE
OPERABLE UNIT 5

RESIDENTIAL AIR, WATER, AND SURFACE SOIL SAMPLE LOCATION MAP

FIGURE 2–7

PLOT DATE/TIME 09/13/2003 02:45:28 PM

FILE I:\hill_afb\dgn\ou5\5ri_803\2_07res1202.dgn

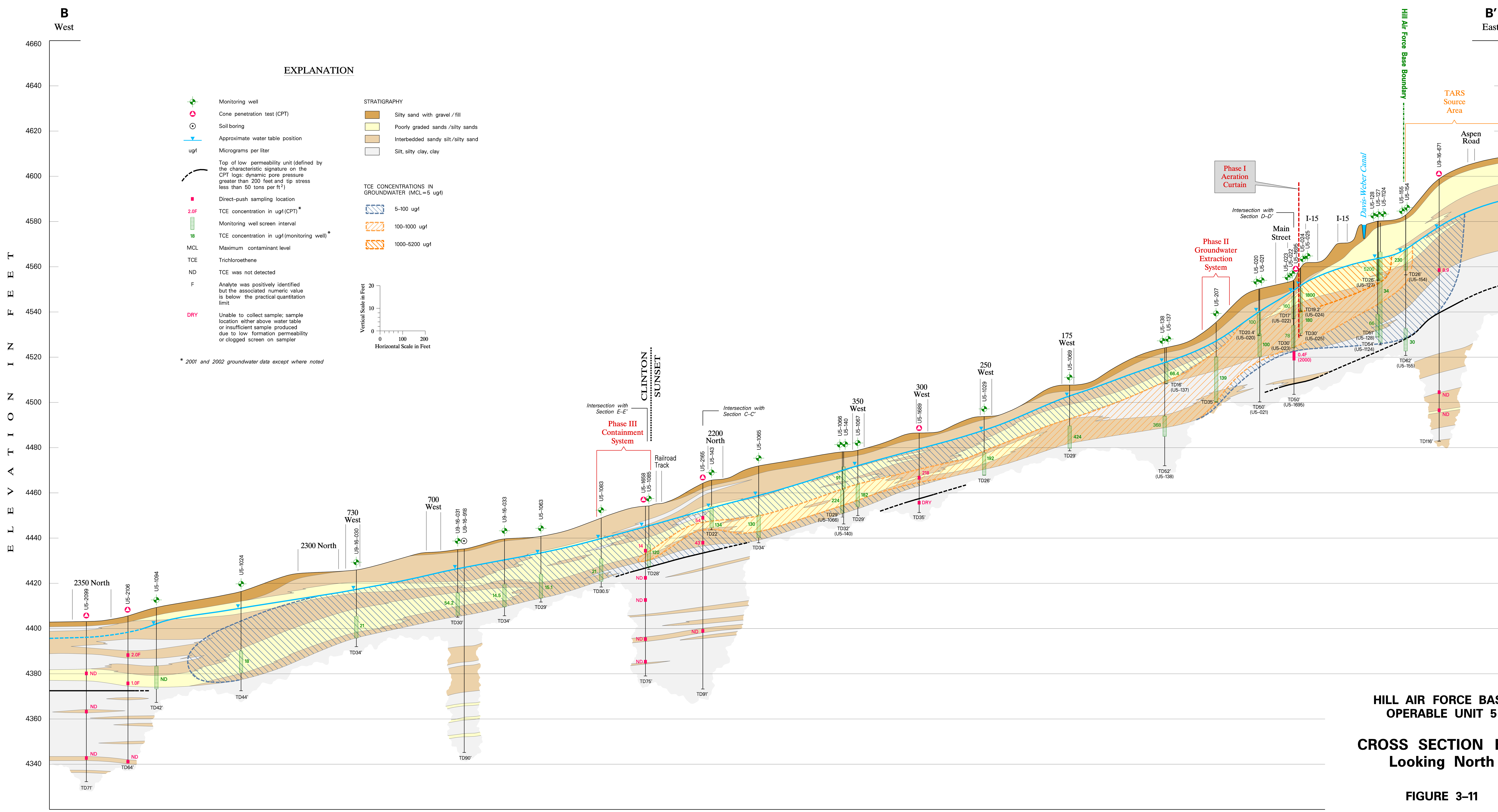


HILL AIR FORCE BASE
OPERABLE UNIT 5
CROSS SECTION LOCATION MAP
FIGURE 3–9
EXPLANATION
Monitoring well
Cone penetration test (CPT)
Deep soil boring
ug/l Micrograms per liter
A⊢⊣A′ Line of cross–section
TRICHLOROETHENE (TCE) CONCENTRATIONS IN GROUNDWATER (2001–2002)
5–10 ug/l
10–100 ug/l
100–1000 ug/l
1000–5200 ug/l
OPERABLE UNIT 12
OPERABLE UNIT 5
Roy
Clinton
Sunset
Meadows Park
Davis–Weber Canal
Hill Air Force Base Boundary
See Detail A
Detail A
Scale in Feet
Scale in Feet
A
A′
B
B′
C
C′
D
D′
E
E′

**HILL AIR FORCE BASE
OPERABLE UNIT 5**

**CROSS SECTION A–A'
Looking North**

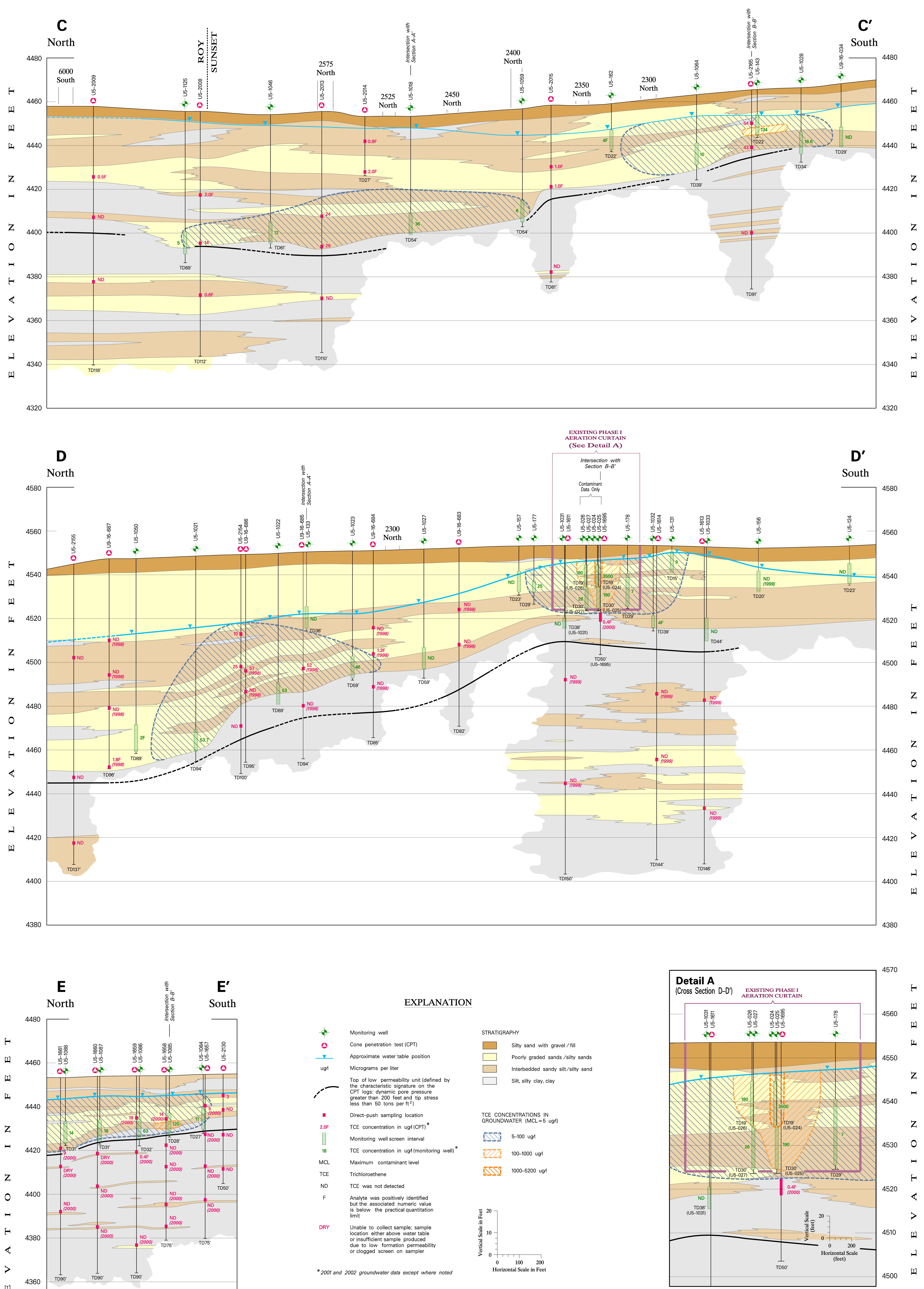
FIGURE 3–10



HILL AIR FORCE BASE
OPERABLE UNIT 5

CROSS SECTION B–B'
Looking North

FIGURE 3–11

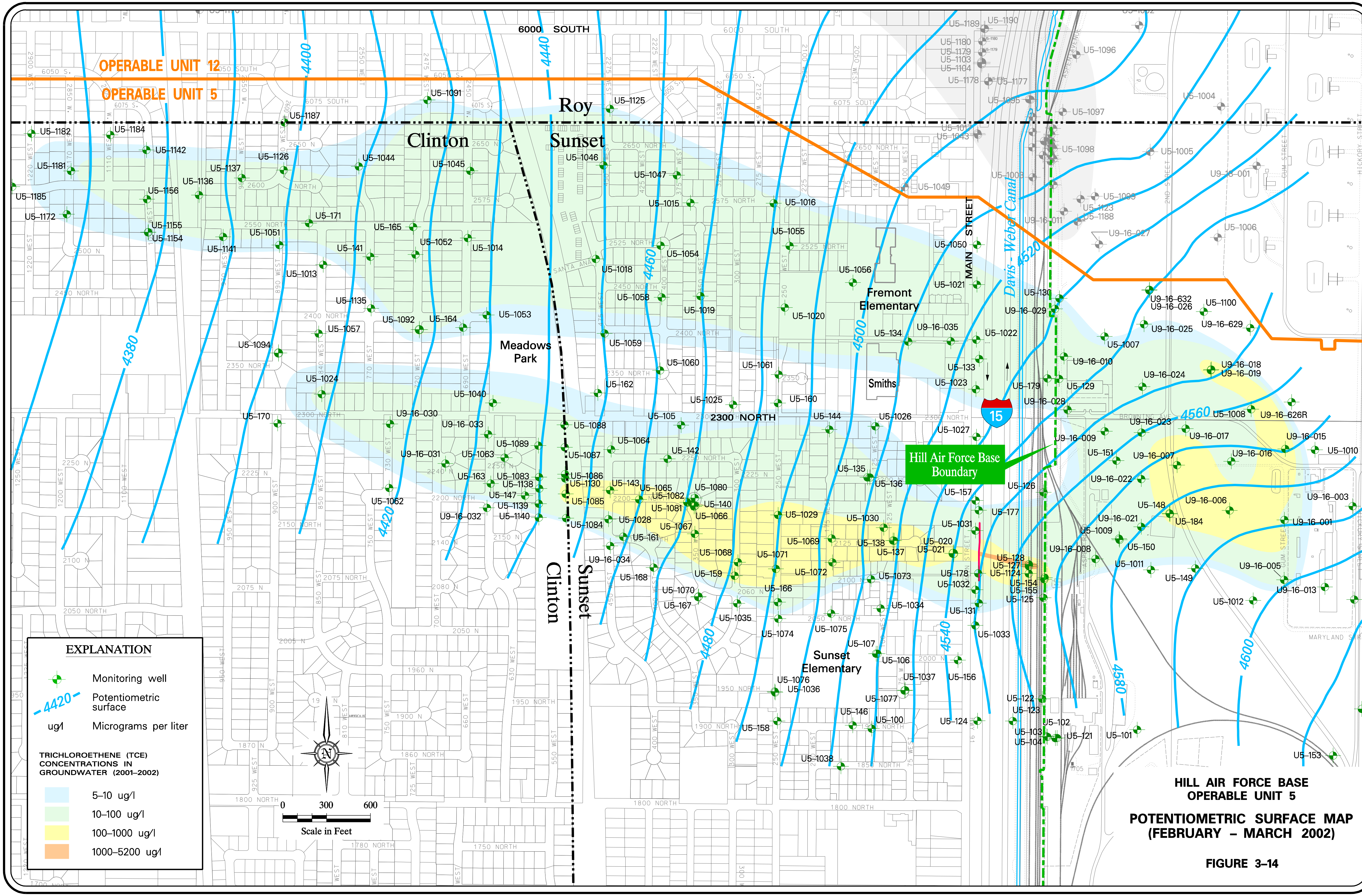


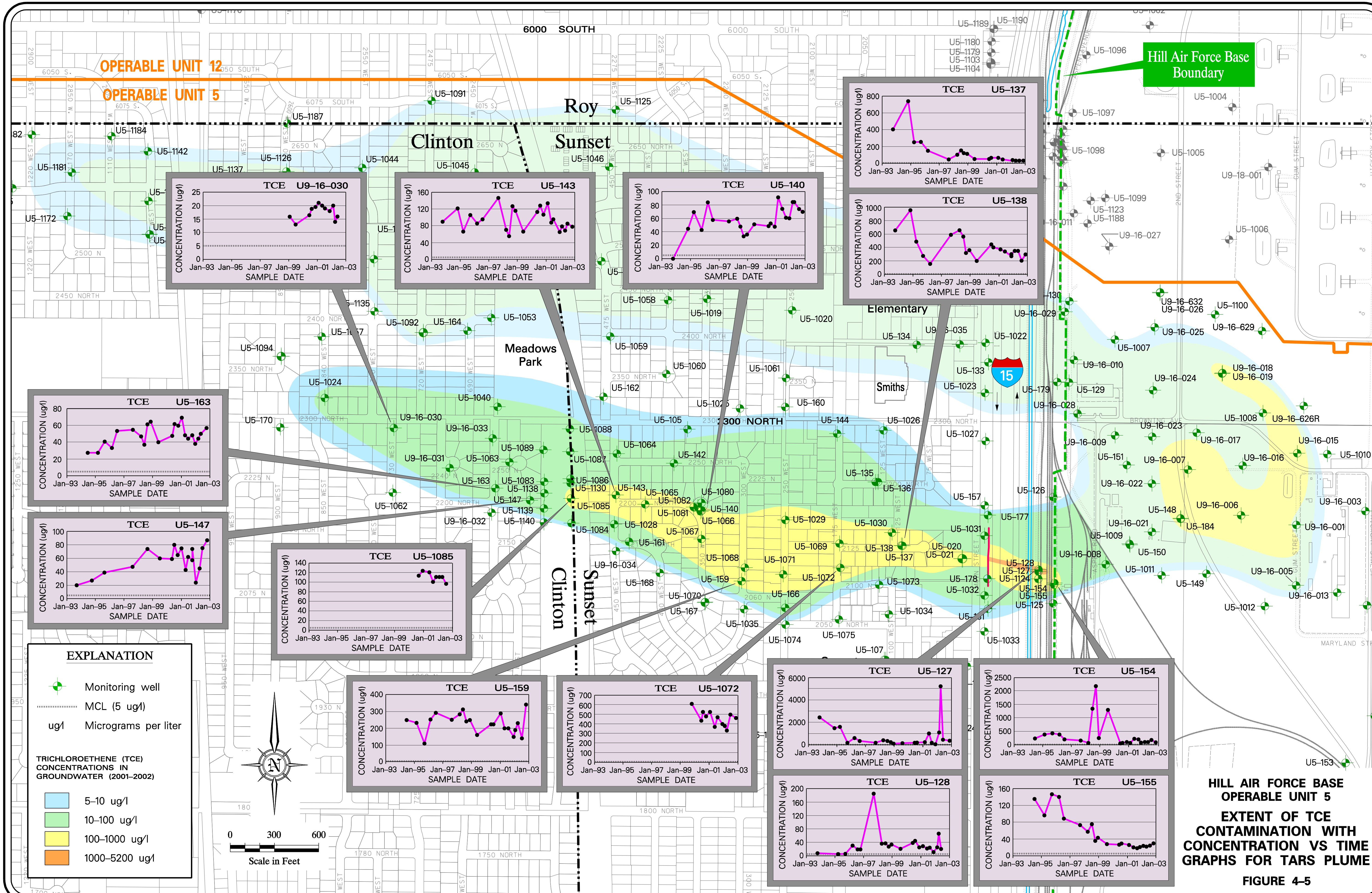
HILL AIR FORCE BASE
OPERABLE UNIT 5

CROSS SECTIONS C–C′, D–D′ and E–E′ Looking East

FIGURE 3–12

FILE I:\hill_afb\dgn\ou5\fri_803\3_14_potsurf1202.dgn PLOT DATE/TIME 09/14/2003 02:20:34 PM





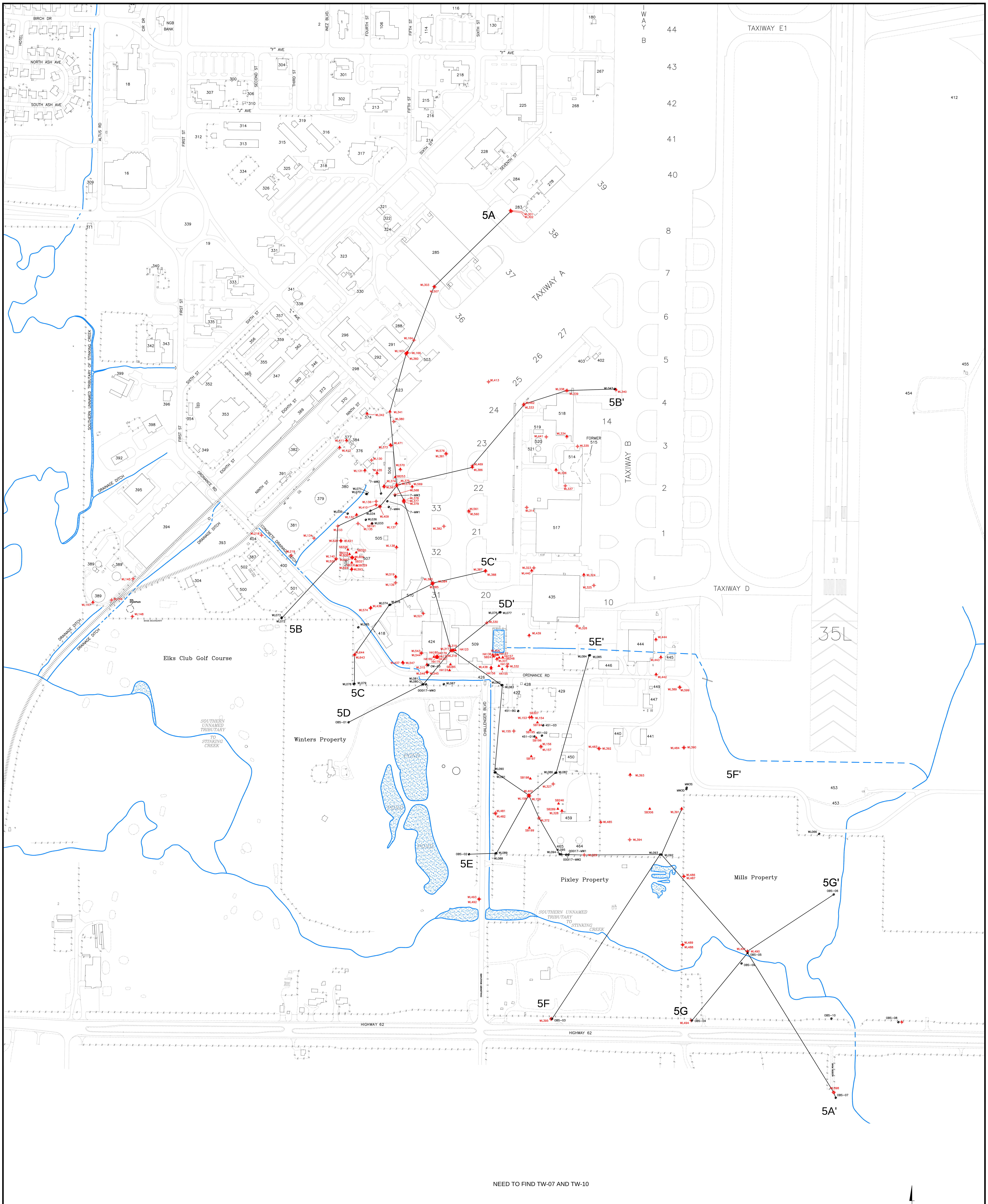
HILL AIR FORCE BASE
OPERABLE UNIT 5

EXTENT OF TCE CONTAMINATION WITH CONCENTRATION VS TIME GRAPHS FOR TARS PLUME

FIGURE 4–5

FILE I:\hill_afb\dgn\ou5\5ri_803\4_05timetar903.dgn

PLOT DATE/TIME 09/23/2003 06:01:41 PM

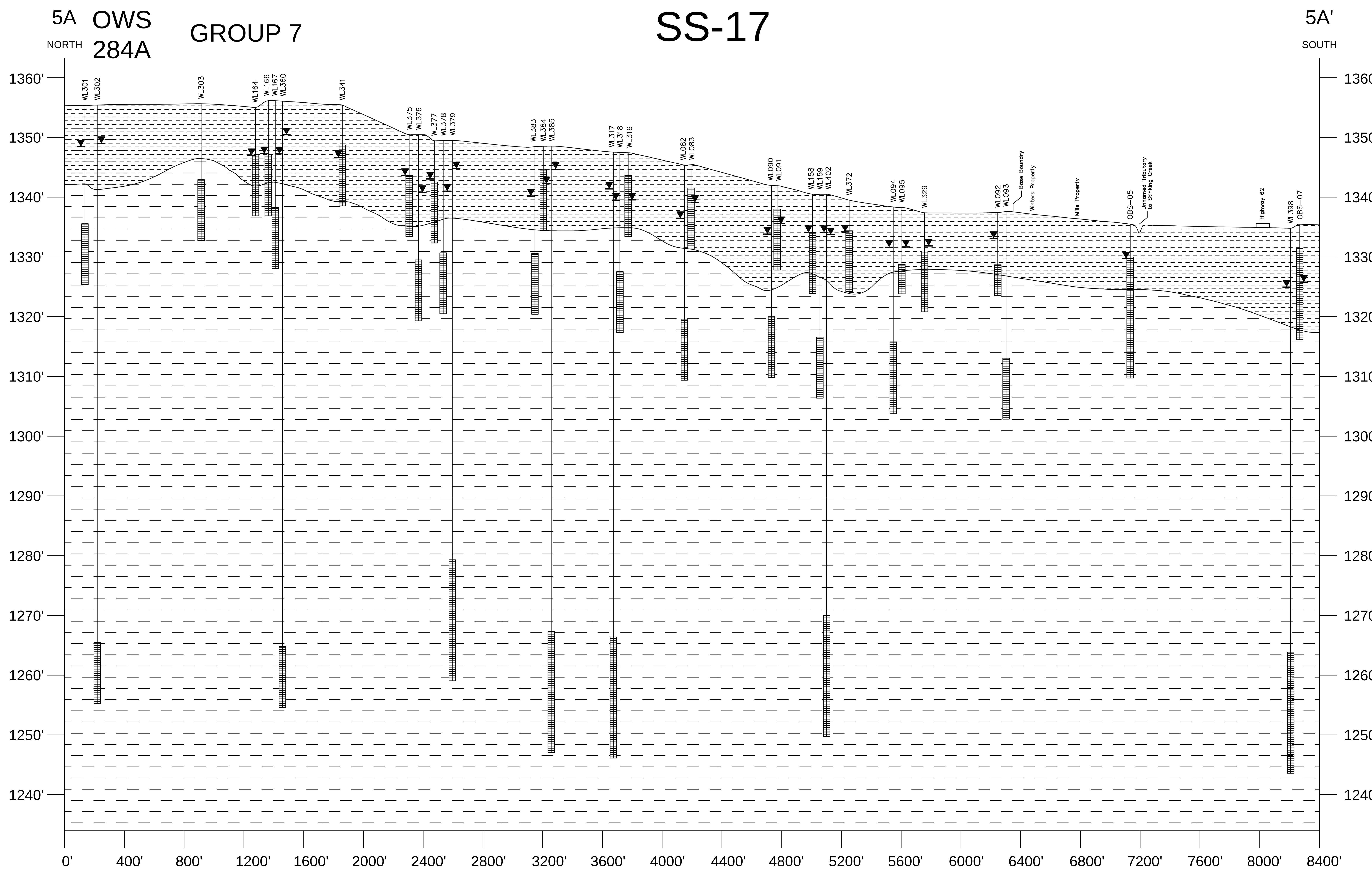


NEED TO FIND TW-07 AND TW-10

LEGEND:
- EXISTING MONITORING WELL
- RFI SOIL BORING
- RFI UPPER MONITORING WELL
- RFI LOWER MONITORING WELL
- RFI DEEP MONITORING WELL

DATE: Oct 14, 2002	SS-17 CROSS-SECTION LOCATION MAP	FIG NO: 4.5.1-2
QC: D. S. Naleid	ALTUS AIR FORCE BASE	

ss-17 sitemap.dwg



LEGEND:

CLAY

RED WEATHERED SHALE

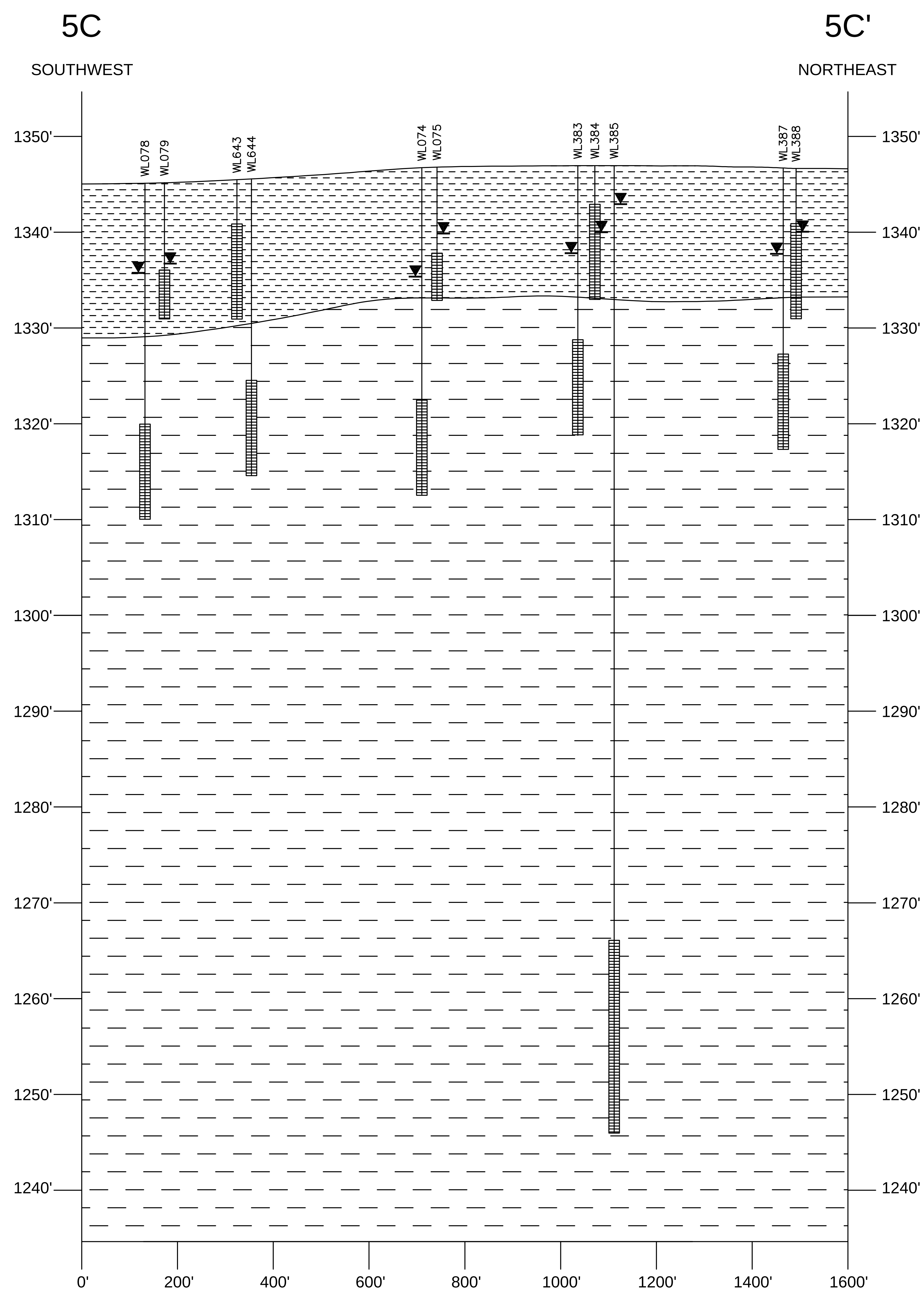
WATER TABLE (MAY 2001)

SCREENED INTERVAL

ss-17 cross 5A.dwg

SCALE:
HORIZONTAL: 1" = 400'
VERTICAL: 1" = 10'
VERTICAL EXAGGERATION: 40X

DATE: Oct 14, 2002	SS-17 GEOLOGIC CROSS-SECTION 5A - 5A' ALTUS AIR FORCE BASE	FIG NO: 4.5.1-3
QC: D. S. Naleid		



LEGEND:

CLAY

RED WEATHERED SHALE

WATER TABLE (MAY 2001)

SCREENED INTERVAL

SCALE:
HORIZONTAL: 1" = 200'
VERTICAL: 1" = 10'
VERTICAL EXAGGERATION: 20X

DATE: Oct 10, 2002	SS-17 GEOLOGIC CROSS-SECTION 5C - 5C' ALTUS AIR FORCE BASE	FIG NO: 4.5.1-5
QC: D. S. Naleid		

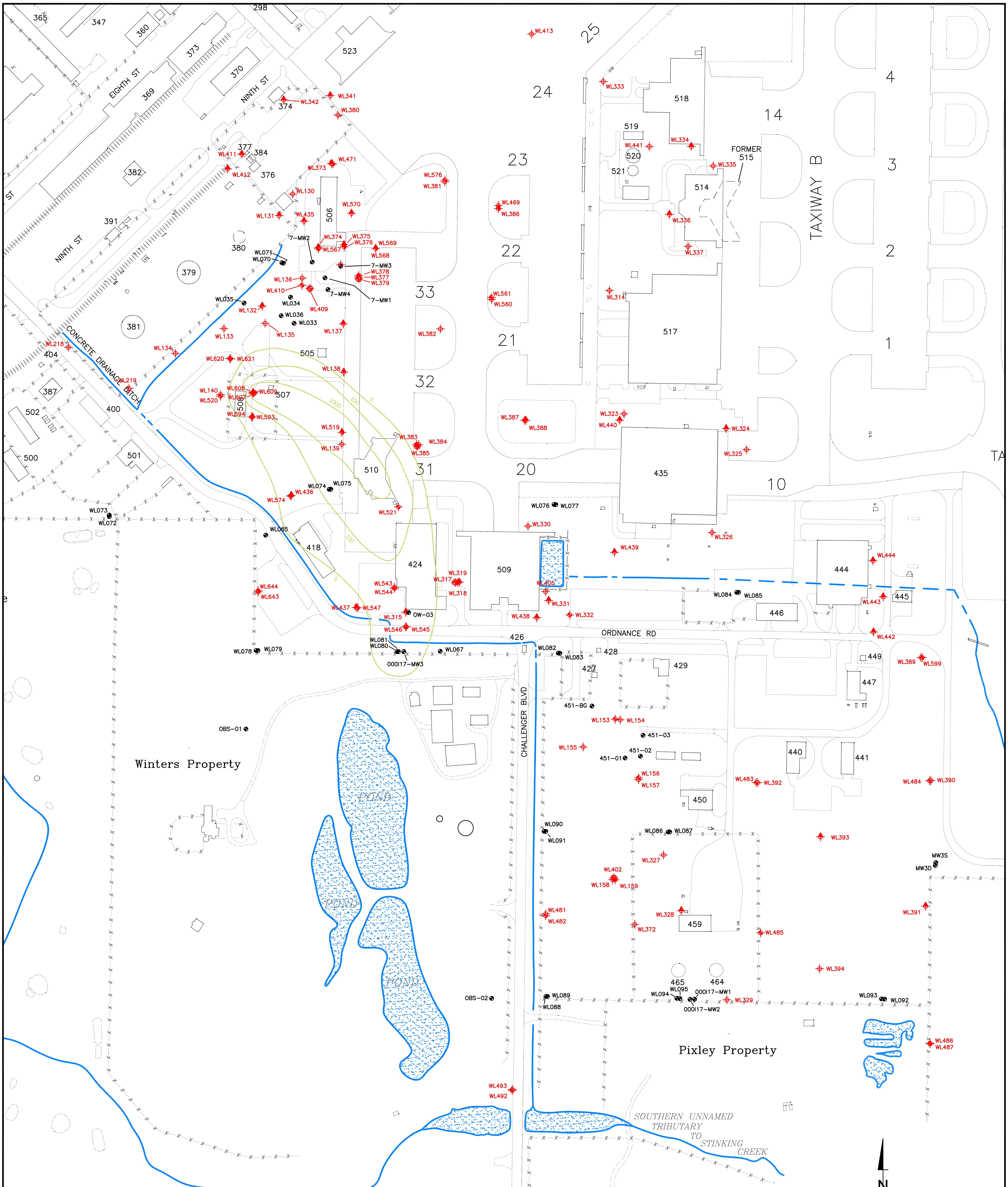
ss-17 cross 5C.dwg

LEGEND:

- EXISTING MONITORING WELL
- RFI SOIL BORING
- RFI UPPER MONITORING WELL
- RFI LOWER MONITORING WELL
- RFI DEEP MONITORING WELL
- TCE CONCENTRATION SS-17 (ug/L) - UPPER
- TCE CONCENTRATION SS-22 (ug/L) - UPPER

ss-17 iso TCE 01 up.dwg

DATE: Sept 26, 2002	SS-17 GROUNDWATER TCE ISOCONCENTRATION MAP UPPER WELLS, 2001 ALTUS AIR FORCE BASE	FIG NO: 4.5.1-17
QC: D. S. Naleid		



LEGEND:

- EXISTING MONITORING WELL
- RFI SOIL BORING
- RFI UPPER MONITORING WELL
- RFI LOWER MONITORING WELL
- RFI DEEP MONITORING WELL
- PCE CONCENTRATION (ug/L) - UPPER

ss-17 iso PCE 01 up.dwg

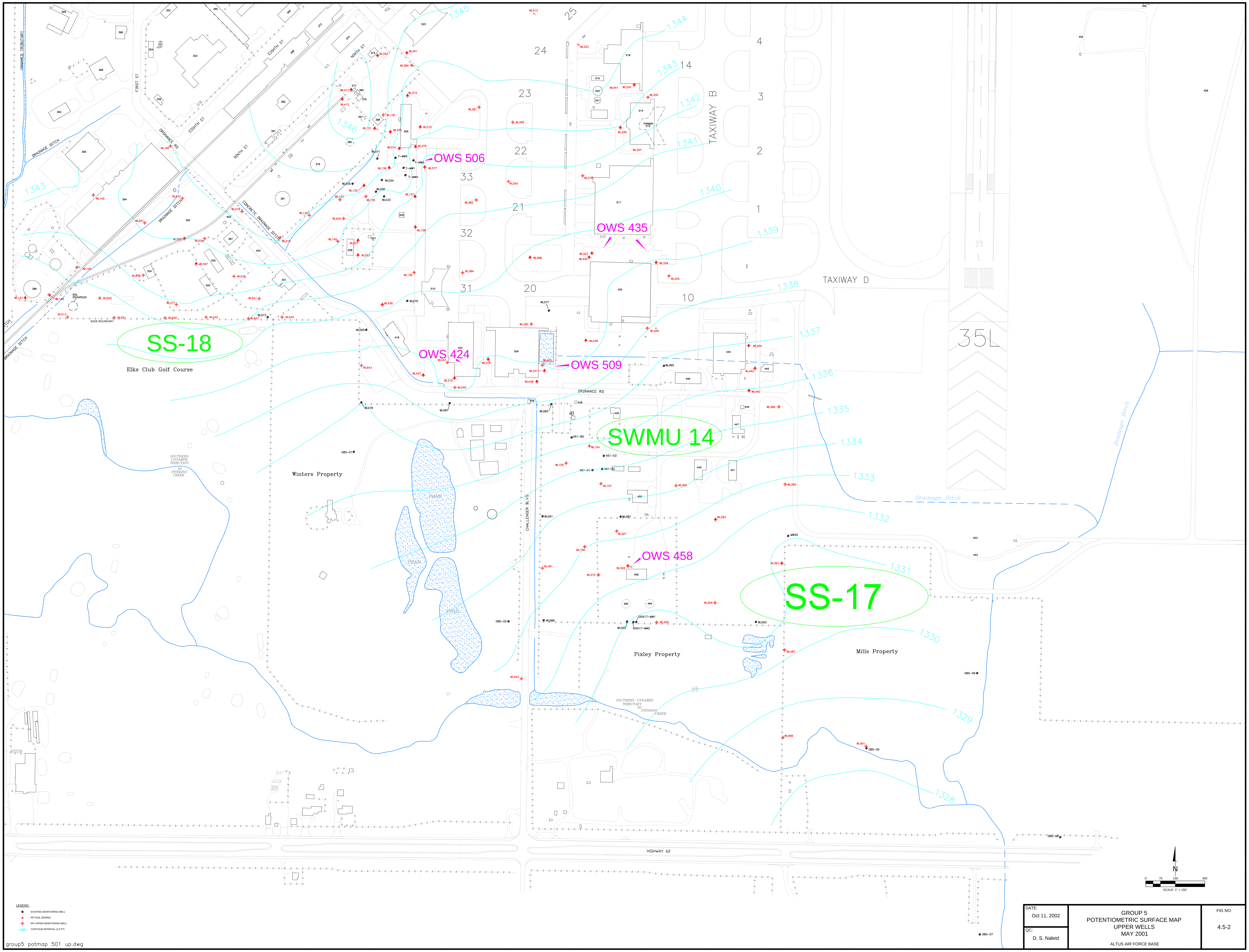
DATE: Sept 24, 2002	SS-17 GROUNDWATER PCE ISOCONCENTRATION MAP UPPER WELLS ALTUS AIR FORCE BASE	FIG NO: 4.5.1-22
QC: D. S. Naleid		

LEGEND:

- EXISTING MONITORING WELL
- RFI SOIL BORING
- RFI UPPER MONITORING WELL
- RFI LOWER MONITORING WELL
- RFI DEEP MONITORING WELL
- DCE CONCENTRATION (ug/L) - UPPER

ss-17 iso DCE 01 up.dwg

DATE: Sept 26, 2002	SS-17 GROUNDWATER DCE ISOCONCENTRATION MAP UPPER WELLS ALTUS AIR FORCE BASE		FIG NO: 4.5.1-20
QC: D. S. Naleid			


OWS 506
OWS 435
OWS 424
OWS 509
OWS 458
SS-18
SWMU 14
SS-17
Elks Club Golf Course
Winters Property
Pixley Property
Mills Property
TAXIWAY B
TAXIWAY D
35L
CHALLENGER BLVD
ORDNANCE RD
HIGHWAY 62
Drainage Ditch
POND
1346
1345
1344
1343
1342
1341
1340
1339
1338
1337
1336
1335
1334
1333
1332
1331
1330
1329
1328
N
SCALE: 1" = 150'
DATE:
Oct 11, 2002
QC:
D. S. Naleid
GROUP 5
POTENTIOMETRIC SURFACE MAP
UPPER WELLS
MAY 2001
ALTUS AIR FORCE BASE
FIG NO:
4.5-2
group5 potmap 501 up.dwg

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix D

Summary of Results from Third Altus AFB Event

GROUNDWATER SERVICES, INC.

TABLE D.1
RESULTS OF GEOTECHNICAL ANALYSES FROM MARCH 2005
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

SAMPLE ID.	SAMPLE DEPTH	BULK DENSITY	FRACTION ORGANIC CARBON	POROSITY			INTRINSIC PERMEABILITY TO WATER	NATIVE HYDRAULIC CONDUCTIVITY
				TOTAL	AIR FILLED	WATER FILLED	25 PSI CONFINING STRESS	
Units	ft.	kg/L	g/g	%Vb	%Vb	%	cm^2	cm/s
MW-2	1-2	1.49	5.55E-03	43.1	13.5	69	4.18E-12	4.05E-07
MW-2	4-5	1.72	1.20E-03	35.1	9.2	74	4.24E-13	4.15E-08
MW-2	7-8	1.6	1.60E-03	40.4	13.9	65	1.87E-12	1.86E-07
MW-6	2-3	1.62	9.20E-03	38.1	11.2	71	2.48E-12	2.45E-07
MW-6	5.5-6.5	1.63	1.50E-03	39.6	14.5	63	1.18E-11	1.18E-06
MW-6	7.5-8.5	1.65	7.90E-04	38.6	10	74	3.35E-12	3.28E-07
MW-10	2-3	1.6	5.05E-03	39.1	13.5	65	2.85E-12	2.76E-07
MW-10	5-6	1.67	1.15E-03	36.7	8.6	77	7.14E-13	6.97E-08
MW-10	7-8	1.63	9.90E-03	39.1	9.7	75	2.30E-12	2.25E-07

Notes:
1) Analysis performed by PTS Laboratories, Houston, Texas.
2) Fraction Organic Carbon determined by Walkley-Black method, intrinsic permeability and hydraulic conductivity determined by EPA 9100, vol. moisture content determined by ASTM D2216 & API RP40, all other analyses by API RP40.
3) All sample orientations were vertical.
4) Vb = bulk volume.

TABLE D.2
RESULTS OF GROUNDWATER ANALYSES: SUMMARY OF DETECTED COMPOUNDS
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

					DUPLICATE		
SAMPLE LOCATION:	MW-1*	MW-2	MW-3*	MW-5	MW-5	MW-7	MW
SCREEN INTERVAL (ft):	9.5-10.5	7.5-8.5	5.5-6.5	9.5-10.5	9.5-10.5	7.5-8.5	9.5-1
SAMPLE TYPE:	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Ground
SAMPLE DATE:	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19
COMPOUND	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/
Compounds of Interest							
Acetone	<0.00087	<0.00087	**0.0175**	<0.00087	<0.00087	<0.00087	**0.003**
cis-1,2-Dichloroethene	<0.00038	**0.00108**	<0.00038	**0.0186**	**0.02**	**0.00906**	**0.01**
trans-1,2-Dichloroethene	<0.00031	<0.00031	<0.00031	**0.00237**	**0.00258**	**0.00436**	<0.00
1,2-Dichloroethane	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	**0.001**
1,2-Dichloroethene (total)	<0.00067	**0.00108**	<0.00067	**0.021**	**0.0226**	**0.0134**	**0.01**
Methyl Ethyl Ketone (2-Butanone)	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108	<0.00
Tetrachloroethene (PCE)	**0.00107**	**0.00263**	<0.00042	**0.00638**	**0.00525**	**0.00205**	<0.00
Trichloroethene (TCE)	**0.00579**	**0.0112**	**0.00139**	**0.105**	**0.108**	**0.0352**	**0.001**

		DUPLICATE					
SAMPLE LOCATION:	MW-10	MW-10	WL-436	WL-437	WL-643	Trip Blank	Field B
SCREEN INTERVAL (ft):	7.5-8.5	7.5-8.5	6.3-16.3	6.3-16.3	4.4-14.4	NA	NA
SAMPLE TYPE:	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Ground
SAMPLE DATE:	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19
COMPOUND	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/
Compounds of Interest							
Acetone	**0.0471**	**0.0456**	<0.00087	<0.00087	<0.00087	<0.00087	<0.00
cis-1,2-Dichloroethene	**0.00178**	**0.00176**	**0.00525**	<0.00038	<0.00038	<0.00038	<0.00
trans-1,2-Dichloroethene	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031	<0.00
1,2-Dichloroethane	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00
1,2-Dichloroethene (total)	**0.00178**	**0.00176**	**0.00525**	<0.00067	<0.00067	<0.00067	<0.00
Methyl Ethyl Ketone (2-Butanone)	**0.00607**	**0.00499**	<0.00108	<0.00108	<0.00108	<0.00108	<0.00
Tetrachloroethene (PCE)	<0.00042	<0.00042	**0.0039**	<0.00042	**0.00158**	<0.00042	<0.00
Trichloroethene (TCE)	<0.00038	<0.00038	**0.00837**	**0.00266**	**0.00698**	<0.00038	<0.00

Notes:
1. All groundwater samples were analyzed by Severn Trent Laboratories, Inc., Houston, Texas by Method 8260B.
2. Screen intervals indicated for WL-436, and WL-437 are estimated based on knowledge of other wells in the area.
3. Detected analytes are presented in bold type.
4. < = not detected at detection limit shown. * = well did not recover after purge, sample collected before purging.
5. NA = not applicable.

GROUNDWATER SERVICES, INC.

TABLE D.3
RESULTS OF WELL HEADSPACE ANALYSES
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	MW-4	MW-6	MW-8	MW-11	MW-12
SCREEN DEPTH (ft bgs):	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE DATE:	3.5-4.5	5.5-6.5	3.5-4.5	5.5-6.5	3.5-4.5
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest					
Acetone	**140**	**330**	**100**	**74**	**98**
Benzene	**3.1**	**1.2**	**1.1**	**1.3**	<0.19
Bromomethane	<1	**22**	<0.65	<0.64	<0.64
2-Butanone (MEK)	**46**	**66**	**9.5**	**10**	**17**
Carbon Disulfide	**3.4**	**3.2**	<0.27	**2.1**	<0.27
Chloroethane	<0.44	**7**	<0.27	<0.27	<0.27
Chloroform	<0.37	**3.5**	<0.23	<0.22	<0.22
Chloromethane	<0.22	**19**	<0.14	<0.13	<0.13
2-Hexanone	**16**	**7.6**	**4**	**1.5**	**6.6**
4-Methyl-2-pentanone	<0.2	**8.3**	<0.12	<0.12	<0.12
m,p -Xylenes	**34**	<0.52	<0.52	<0.51	<0.51
o-Xylene	**14**	<0.29	<0.29	<0.29	<0.29
Tetrachloroethene (PCE)	**81**	**120**	**38**	**25**	**43**
Toluene	**12**	**1.3**	<0.24	**1.9**	<0.23
Trichloroethene (TCE)	**5.9**	**560**	<0.18	**12**	**10**
Trichlorofluoromethane	<0.24	**1.6**	<0.15	<0.15	<0.15
Trichlorotrifluoroethane	**76**	**59**	**6.3**	**4.2**	**2.3**

NOTES:
1. Sample locations are presented on Figure D.1.
2. Samples were collected in 1L Summa canisters back filled with 600 ml nitrogen, and were analyzed by Columbia Analytical Services, Simi Valley, California by method TO-15.
3. Detected analytes are presented in bold type.
4. < = Not detected at the detection limit shown.

GROUNDWATER SERVICES, INC.

TABLE D.4
RESULTS OF SOIL-GAS ANALYSES
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	SG-4	SG-5	SG-6	SG-7	SG-8
SCREEN DEPTH (ft bgs):	4	1	2	3	4
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest					
Acetone	**85**	**120**	**79**	**66**	**72**
Benzene	<0.27	<0.18	<0.19	<0.19	**1.2**
2-Butanone (MEK)	**28**	**22**	**19**	**11**	**13**
Carbon Disulfide	**5.7**	**2.1**	**1.7**	**2.2**	**3.5**
Chloromethane	<0.19	<0.13	**1.2**	<0.13	**1.8**
cis-1,2-Dichloroethene	<0.23	<0.16	<0.17	<0.16	<0.17
1,1-Dichloroethene	<0.2	<0.14	<0.15	<0.14	**1.5**
Ethylbenzene	<0.34	<0.24	<0.25	<0.24	<0.25
2-Hexanone	**9.2**	**3.1**	**3.8**	**3.9**	**3.5**
m,p-Xylenes	<0.72	<0.5	<0.52	<0.5	<0.53
o- Xylene	<0.41	<0.28	<0.29	<0.28	<0.3
Tetrachloroethene (PCE)	**87**	**4.1**	**19**	**33**	**40**
Toluene	<0.33	<0.23	<0.24	<0.23	<0.24
trans-1,2-Dichloroethene	<0.33	<0.23	<0.24	<0.23	<0.24
Trichloroethene	<0.25	<0.17	<0.18	<0.17	<0.18
1,1,1-Trichloroethane	<0.14	<0.099	<0.1	<0.099	**9.8**
Trichlorofluoromethane	**3.2**	<0.14	<0.15	**1.2**	**1.2**
Trichlorotrifluoroethane	**120**	**1.8**	**4.9**	**6.5**	**7**
Vinyl Chloride	<0.34	<0.24	<0.25	<0.24	<0.25

SAMPLE LOCATION:	Duplicate SG-8	SG-9	SG-10	SG-11	SG-12
SCREEN DEPTH (ft bgs):	4	1	2	3	4
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest					
Acetone	**100**	**82**	<0.82	**78**	**100**
Benzene	<0.19	<0.19	<0.2	<0.2	**4.6**
2-Butanone (MEK)	**22**	**27**	**14**	**20**	**26**
Carbon Disulfide	**9**	**1.4**	**1.5**	<0.28	**1.5**
Chloromethane	<0.13	<0.14	<0.14	<0.14	<0.15
cis-1,2-Dichloroethene	<0.17	<0.17	<0.18	<0.17	<0.19
1,1-Dichloroethene	<0.14	<0.15	<0.15	<0.15	<0.16
Ethylbenzene	<0.25	<0.25	<0.26	<0.26	**6.5**
2-Hexanone	**6.2**	**6.3**	**2.3**	**4.6**	**5**
m,p-Xylenes	<0.51	<0.52	<0.54	<0.54	**66**

GROUNDWATER SERVICES, INC.

TABLE D.5
RESULTS OF SUB-SLAB ANALYSES
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	SS-1	SS-2	SS-3
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006
COMPOUND	ug/m3	ug/m3	ug/m3
Compounds of Interest			
Acetone	**58**	**86**	**94**
2-Butanone (MEK)	**17**	**23**	**26**
Carbon Disulfide	**3.7**	**1.9**	**10**
cis-1,2-Dichloroethene	<0.17	<0.17	<0.18
trans-1,2-Dichloroethene	<0.24	<0.24	<0.25
2-Hexanone	**3.3**	**5.7**	**10**
Tetrachloroethene (PCE)	**480**	**540**	**33**
Toluene	<0.24	<0.24	**1.4**
Trichloroethene (TCE)	**29**	**33**	**1.8**
Trichlorofluoromethane	**20**	**21**	**1.8**
Trichlorotrifluoroethane	**540**	**590**	**6**
Vinyl Chloride	<0.25	<0.26	<0.27

NOTES:
1. Sample locations are presented on Figure D.1.
2. Samples were collected in 1L Summa canisters back filled with 600 ml nitrogen, and were analyzed by Columbia Analytical Services, Simi Valley, California by method TO-15.
3. Detected analytes are presented in bold type.
4. < = Not detected at the detection limit shown.

GROUNDWATER SERVICES, INC.

TABLE D.6
RESULTS OF INDOOR AND AMBIENT AIR ANALYSES
ESTCP: Vapor Intrusion Study

Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	Indoor 1	Indoor 2	Indoor 2 dup (DUPLICATE)	Indoor 3	Ambient 1	Ambient 2	Ambient 3
SAMPLE TYPE:	Indoor air	Indoor air	Indoor air	Indoor air	Ambient air	Ambient air	Ambient air
SAMPLE DATE:	12/20/2006	12/20/2006	12/20/2006	12/20/2006	12/20/2006	12/20/2006	12/20/2006
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest							
Benzene	**0.71**	**0.75**	**0.77**	**0.8**	**0.73**	**0.72**	**0.77**
1,1-Dichloroethene	<0.0049	<0.0055	<0.0059	<0.0064	<0.0056	<0.0051	<0.0045
cis-1,2-Dichloroethene	<0.0044	<0.0049	<0.0052	<0.0057	<0.005	<0.0046	<0.004
trans-1,2-Dichloroethene	<0.0046	<0.0052	<0.0056	<0.006	<0.0053	<0.0049	<0.0043
Ethylbenzene	**0.44**	**0.59**	**0.63**	**0.74**	**0.3**	**0.44**	**0.56**
m,p-Xylenes	**1.1**	**1.4**	**1.6**	**1.8**	**0.87**	**1.2**	**1.4**
o-Xylene	**0.42**	**0.51**	**0.55**	**0.7**	**0.33**	**0.45**	**0.52**
Tetrachloroethene (PCE)	**0.36**	**0.63**	**0.59**	**0.28**	**0.14**	**0.15**	**0.21**
Toluene	**4.1**	**6.7**	**7.6**	**7**	**2.4**	**4.1**	**6.4**
Trichloroethene (TCE)	**0.1**	**0.18**	**0.18**	**0.12**	**0.047**	**0.056**	**0.087**
Vinyl Chloride	<0.0026	<0.0029	<0.0031	<0.0034	<0.003	<0.0027	<0.0024

NOTES:
1. Sample locations are presented on Figure D.1.
2. Samples were analyzed by Columbia Analytical Services, Simi Valley, California by method TO-15 SIM.
3. Detected analytes are presented in **bold** type.
4. < = not detected at detection limit shown.

GROUNDWATER SERVICES, INC.

TABLE D.7
RESULTS OF SULFUR HEXAFLUORIDE TRACER GAS ANALYSES
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

Tedlar Tracer gas samples

SAMPLE LOCATION:	Indoor 1	Indoor 2	Indoor 3	Indoor 4	Indoor 5
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	8:20 AM	8:22 AM	8:24 AM	8:26 AM	8:28 AM
COMPOUND	ppmv	ppmv	ppmv	ppmv	ppmv
Compounds of Interest					
Sulfur Hexafluoride (SF6)	2.9	4.1	10	3.4	3.7

24 hr composite samples

			Duplicate	
SAMPLE LOCATION:	Indoor 1	Indoor 2	Indoor 2	Indoor 3
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	8:15 AM	8:15 AM	8:15 AM	8:15 AM
COMPOUND	ppmv	ppmv	ppmv	ppmv
Compounds of Interest				
Sulfur Hexafluoride (SF6)	5.9	5.7	5.4	13

			Duplicate	
SAMPLE LOCATION:	SS-1	SS-2	SS-2	SS-3
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	8:45 AM	9:05 AM	8:55 AM	9:15 AM
COMPOUND	ppmv	ppmv	ppmv	ppmv
Compounds of Interest				
Sulfur Hexafluoride (SF6)	0.095	0.22	0.076	0.31

SAMPLE LOCATION:	SG-9	SG-10	SG-11	SG-12
SAMPLE DATE:	12/16/2006	12/16/2006	12/16/2006	12/16/2006
SAMPLE TIME:	10:01 AM	10:07 AM	10:10 AM	10:15 AM
COMPOUND	ppmv	ppmv	ppmv	ppmv
Compounds of Interest				
Sulfur Hexafluoride (SF6)	0.71	0.2	0.12	0.28

Soil Gas Analysis Leak Tracer

						Duplicate
SAMPLE LOCATION:	SG-4	SG-5	SG-6	SG-7	SG-8	SG-8
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	11:15 AM	12:30 AM	12:35 AM	12:40 AM	12:45 AM	12:50 AM
COMPOUND	ppmv	ppmv	ppmv	ppmv	ppmv	ppmv
Compounds of Interest						

GSI Job No. G-2882
Issued: 3/2/2007

TABLE D.8
RESULTS OF RADON ANALYSES
ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	SG-5	SG-6	SG-7	SG-8	SG-9	SG-10	SG-11
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/20
SAMPLE TIME:	12:30	12:35	12:40	12:45	10:01	10:07	10:10
COLLECT/COUNT IN:	58/31	61/33	B13/32	58/31	61/33	Z13/31	SC6/33
VOLUME (cc):	20	20	20	20	20	40	40
CELL dpm/L:	806	1651	1930	1957	894	2371	2502
COMPOUND	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L
Compound of Interest							
Radon	363	744	869	881	403	1068	1127

		Duplicate			*Duplicate*
SAMPLE LOCATION:	SS-1	SS-1	SS-2	SS-3	SS-3
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	8:45	8:45	9:05	9:15	9:15
COLLECT/COUNT IN:	58/31	60/32	61/33	Z13/31	SC6/33
VOLUME (cc):	20	40	20	40	40
CELL dpm/L:	2066	2224	2105	430	427
COMPOUND	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L
Compound of Interest					
Radon	931	1002	948	194	192

		Duplicate			
SAMPLE LOCATION:	Ambient	Ambient	Indoor-1	Indoor-2	Indoor-3
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
SAMPLE TIME:	9:28	9:28	9:30	9:32	9:33
COLLECT/COUNT IN:	81/31	81/31	82/33	82/33	82/33
VOLUME (cc):	120	120	120	120	120
CELL dpm/L:	0.6	0.7	1.5	2	1.9
COMPOUND	pCi/L	pCi/L	pCi/L	pCi/L	pCi/L
Compound of Interest					
Radon	0.3	0.3	0.7	0.9	0.9

NOTES:

1. Sample locations are presented on Figure D.1.
2. Uncertainty for a single analysis is ±5% or 0.1 pCi/L, whichever is larger (high activity samples).
3. Radon samples were analyzed by Doug Hammond, University of Southern California.

GROUNDWATER SERVICES, INC.

TABLE D.9
STATIC WATER LEVEL MEASUREMENTS
ESTCP Vapor Intrusion Study
Altus Air Force Base
Altus, Oklahoma

		3/21/2005	3/23/2005	7/10/2006	12/19/2006
Well No.	**Installed Total Depth ft, bgs**	**Depth to Water ft, bgs**	**Depth to Water ft, bgs**	**Depth to Water ft, bgs**	**Depth to Water ft, bgs**
MW-1	10.5	DRY	10.30	6.45	7.50
MW-2	8.5	DRY	DRY	6.45	6.8
MW-3	6.5	6.40	DRY	6.21	5.86
MW-4	4.5	DRY	DRY	DRY	4.28
MW-5	10.5	5.70	6.20	7.88	7.73
MW-6	6.5	6.20	6.30	DRY	DRY
MW-7	8.5	5.70	6.10	7.89	7.55
MW-8	4.5	DRY	DRY	DRY	DRY
MW-9	10.5	9.50	10.00	7.6	7.65
MW-10	8.5	DRY	DRY	7.61	7.4
MW-11	6.5	DRY	DRY	DRY	DRY
MW-12	4.5	DRY	DRY	DRY	DRY
WL-436	16.3	6.55	nm	8.6	8.2
WL-437	16.3	5.30	nm	7.2	6.45
WL-643	14.4	5.40	nm	7.81	7.36

NOTES:
1. Sample locations are presented on Figure D.1.
2. bgs = below ground surface
   nm = not measured

GROUNDWATER SERVICES, INC.

TABLE D.10
RESULTS OF SULFUR HEXAFLUORIDE LEAK TRACER ANALYSES
ESTCP: Vapor Intrusion Study

Altus Air Force Base, Altus, Oklahoma

Building 418				
Sample Location	Tracer Used	Result ug/m^3	Result ppbV	% Leakage
Indoor 1	No	35,907	5,900	NA
Indoor 2	No	34,690	5,700	NA
Indoor 2 Dup	No	32,864	5,400	NA
Indoor 3	No	79,118	13,000	NA
SG-4	Yes	11,563,400	1,900,000	3.85%
SG-5	Yes	9,738	1,600	0.00%
SG-6	Yes	2,008	330	0.00%
SG-7	Yes	1,217	200	0.00%
SG-8	Yes	913	150	0.00%
SG-8 Dup	Yes	1,156	190	0.00%
SG-9	No	4,321	710	NA
SG-10	No	1,217	200	NA
SG-11	No	730	120	NA
SG-12	No	1,704	280	NA
SS-1	No	578	95	NA
SS-2	No	1,339	220	NA
SS-2 Dup	No	463	76	NA
SS-3	No	1,887	310	NA
HS-4	Yes	45,036,400	7,400,000	15.01%
HS-6	Yes	243,440	40,000	0.08%
HS-8	Yes	1,217	200	0.00%
HS-11	Yes	31,647	5,200	0.01%
HS-12	Yes	6,086	1,000	0.00%

NOTES:
1. Sample locations are presented on Figure D.1.
2. % leakage = SF6 concentration / 300,000,000
3. Samples were analyzed by Columbia Analytical Services, Simi Valley, California.
4. ND = not detected. N/A = not applicable (no leak tracer used).

GROUNDWATER SERVICES, INC.

TABLE D.11
RESULTS OF GROUNDWATER ANALYSES
ESTCP: Vapor Intrusion Study

Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	MW-1*	MW-2	MW-3*	MW-5	MW-5 *DUPLICATE*	MW-7	MW-9	MW-10	MW-10 *DUPLICATE*	WL-436	WL-437	WL-643	Trip Blank	Field Blank
SCREEN INTERVAL (ft BGS):	9.5-10.5	7.5-8.5	5.5-6.5	9.5-10.5	9.5-10.5	7.5-8.5	9.5-10.5	7.5-8.5	7.5-8.5	6.3-16.3	6.3-16.3	4.4-14.4	NA	NA
SAMPLE TYPE:	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater	Groundwater
SAMPLE DATE:	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06	12/19/06
COMPOUND	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Compounds of Interest														
Acetone	<0.00087	<0.00087	**0.0175**	<0.00087	<0.00087	<0.00087	**0.00361**	**0.0471**	**0.0456**	<0.00087	<0.00087	<0.00087	<0.00087	<0.00087
Benzene	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038	<0.00038
Bromodichloromethane	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042
Bromoform	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065	<0.00065
Bromomethane	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021	<0.00021
Carbon Disulfide	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047
Carbon Tetrachloride	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027	<0.00027
Chlorobenzene	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Chloroethane	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059	<0.00059
Chloroform	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028
Chloromethane	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047
Dibromochloromethane	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
1,1-Dichloroethane	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044
1,2-Dichloroethane	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	**0.00179**	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047	<0.00047
1,1-Dichloroethene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
cis-1,2-Dichloroethene	<0.00038	**0.00108**	<0.00038	**0.0186**	**0.02**	**0.00906**	**0.0122**	**0.00178**	**0.00176**	**0.00525**	<0.00038	<0.00038	<0.00038	<0.00038
trans-1,2-Dichloroethene	<0.00031	<0.00031	<0.00031	**0.00237**	**0.00258**	**0.00436**	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031	<0.00031
1,2-Dichloroethene (total)	<0.00067	**0.00108**	<0.00067	**0.021**	**0.0226**	**0.0134**	**0.0122**	**0.00178**	**0.00176**	**0.00525**	<0.00067	<0.00067	<0.00067	<0.00067
1,2-Dichloropropane	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039	<0.00039
cis-1,3-Dichloropropene	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042
trans-1,3-Dichloropropene	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Ethylbenzene	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037	<0.00037
2-Hexanone	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075	<0.00075
Methylene Chloride	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056	<0.00056
Methyl Ethyl Ketone (2-Butanone)	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108	**0.00607**	**0.00499**	<0.00108	<0.00108	<0.00108	<0.00108	<0.00108
4-Methyl-2-pentanone (MIBK)	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006
Styrene	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034
1,1,2,2-Tetrachloroethane	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042	<0.00042
Tetrachloroethene (PCE)	**0.00107**	**0.00263**	<0.00042	**0.00638**	**0.00525**	**0.00205**	<0.00042	<0.00042	<0.00042	**0.0039**	<0.00042	**0.00158**	<0.00042	<0.00042
Toluene	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
1,1,1-Trichloroethane	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028	<0.00028
1,1,2-Trichloroethane	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062	<0.00062
Trichloroethene (TCE)	**0.00579**	**0.0112**	**0.00139**	**0.105**	**0.108**	**0.0352**	**0.00121**	<0.00038	<0.00038	**0.00837**	**0.00266**	**0.00698**	<0.00038	<0.00038
Vinyl Chloride	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034	<0.00034
Xylenes (total)	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095	<0.00095

NOTES:
1. All groundwater samples were analyzed by Severn Trent Laboratories, Inc., Houston, Texas Method 8260B.
2. Screen intervals indicated for WL-436, and WL-437 are estimated based on knowledge of other wells in the area.
3. Detected analytes are presented in **bold** type.
4. < = not detected at detection limit shown. * = well did not recover after purge, sample collected before purging.

GROUNDWATER SERVICES, INC.

TABLE D.12
RESULTS OF TO-15 ANALYSES
ESTCP: Vapor Intrusion Study

Altus Air Force Base, Altus, Oklahoma

						Duplicate				
SAMPLE LOCATION:	SG-4	SG-5	SG-6	SG-7	SG-8	SG-8	SG-9	SG-10	SG-11	SG-12
SAMPLE TYPE:	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas	Soil Gas
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
NG/SCREEN DEPTH (ft bgs):	4	1	2	3	4	4	1	2	3	4
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest										
Acetone	**85**	**120**	**79**	**66**	**72**	**100**	**82**	<0.82	**78**	**100**
Benzene	<0.27	<0.18	<0.19	<0.19	**1.2**	<0.19	<0.19	<0.2	<0.2	**4.6**
Bromodichloromethane	<0.2	<0.14	<0.15	<0.14	<0.15	<0.14	<0.15	<0.15	<0.15	<0.16
Bromoform	<0.44	<0.3	<0.32	<0.31	<0.32	<0.31	<0.32	<0.33	<0.33	<0.35
Bromomethane	<0.89	<0.62	<0.64	<0.62	<0.65	<0.64	<0.65	<0.67	<0.66	<0.72
2-Butanone (MEK)	**28**	**22**	**19**	**11**	**13**	**22**	**27**	**14**	**20**	**26**
Carbon Disulfide	**5.7**	**2.1**	**1.7**	**2.2**	**3.5**	**9**	**1.4**	**1.5**	<0.28	**1.5**
Carbon Tetrachloride	<0.25	<0.17	<0.18	<0.17	<0.18	<0.18	<0.18	<0.19	<0.19	<0.2
Chlorobenzene	<0.39	<0.27	<0.28	<0.27	<0.29	<0.28	<0.29	<0.29	<0.29	<0.32
Chloroethane	<0.38	<0.26	<0.27	<0.26	<0.27	<0.27	<0.27	<0.28	<0.28	<0.3
Chloroform	<0.31	<0.22	<0.23	<0.22	<0.23	<0.22	<0.23	<0.23	<0.23	<0.25
Chloromethane	<0.19	<0.13	**1.2**	<0.13	**1.8**	<0.13	<0.14	<0.14	<0.14	<0.15
1,2-Dibromoethane	<0.39	<0.27	<0.28	<0.27	<0.29	<0.28	<0.29	<0.29	<0.29	<0.32
1,2-Dichlorobenzene	<0.44	<0.3	<0.32	<0.31	<0.32	<0.31	<0.32	<0.33	<0.33	<0.35
1,3-Dichlorobenzene	<0.41	<0.28	<0.29	<0.28	<0.3	<0.29	<0.3	<0.3	<0.3	<0.33
1,4-Dichlorobenzene	<0.36	<0.25	<0.26	<0.25	<0.26	<0.26	<0.26	<0.27	<0.27	<0.29
1,1-Dichloroethane	<0.22	<0.15	<0.16	<0.15	<0.16	<0.16	<0.16	<0.16	<0.16	<0.18
1,2-Dichloroethane	<0.28	<0.19	<0.2	<0.2	<0.21	<0.2	<0.21	<0.21	<0.21	<0.23
1,1-Dichloroethene	<0.2	<0.14	<0.15	<0.14	**1.5**	<0.14	<0.15	<0.15	<0.15	<0.16
cis-1,2-Dichloroethene	<0.23	<0.16	<0.17	<0.16	<0.17	<0.17	<0.17	<0.18	<0.17	<0.19
trans-1,2-Dichloroethene	<0.33	<0.23	<0.24	<0.23	<0.24	<0.23	<0.24	<0.25	<0.24	<0.26
1,2-Dichloropropane	<0.22	<0.15	<0.16	<0.15	<0.16	<0.16	<0.16	<0.16	<0.16	<0.18
cis-1,3-Dichloropropene	<0.27	<0.18	<0.19	<0.19	<0.19	<0.19	<0.19	<0.2	<0.2	<0.21
trans-1,3-Dichloropropene	<0.19	<0.13	<0.14	<0.13	<0.14	<0.13	<0.14	<0.14	<0.14	<0.15
Dibromochloromethane	<0.33	<0.23	<0.24	<0.23	<0.24	<0.23	<0.24	<0.25	<0.24	<0.26
Ethylbenzene	<0.34	<0.24	<0.25	<0.24	<0.25	<0.25	<0.25	<0.26	<0.26	**6.5**
2-Hexanone	**9.2**	**3.1**	**3.8**	**3.9**	**3.5**	**6.2**	**6.3**	**2.3**	**4.6**	**5**
m,p-Xylenes	<0.72	<0.5	<0.52	<0.5	<0.53	<0.51	<0.52	<0.54	<0.54	**66**
4-Methyl-2-pentanone	<0.17	<0.12	<0.12	<0.12	<0.13	<0.12	<0.13	<0.13	<0.13	<0.14
Methyl tert-Butyl Ether	<0.36	<0.25	<0.26	<0.25	<0.26	<0.26	<0.26	<0.27	<0.27	<0.29
Methylene chloride	<0.34	<0.24	<0.25	<0.24	<0.25	<0.25	<0.25	<0.26	<0.26	<0.28
o-Xylene	<0.41	<0.28	<0.29	<0.28	<0.3	<0.29	<0.3	<0.3	<0.3	**22**
Styrene	<0.27	<0.18	<0.19	<0.19	<0.19	<0.19	<0.19	<0.2	<0.2	<0.21
1,1,2,2-Tetrachloroethane	<0.38	<0.26	<0.27	<0.26	<0.27	<0.27	<0.27	<0.28	<0.28	<0.3
Tetrachloroethene (PCE)	**87**	**4.1**	**19**	**33**	**40**	**34**	**43**	**59**	**140**	**180**
Toluene	<0.33	<0.23	<0.24	<0.23	<0.24	<0.23	<0.24	<0.25	<0.24	**33**
1,1,1-Trichloroethane	<0.14	<0.099	<0.1	<0.099	**9.8**	<0.1	<0.1	<0.11	**1.5**	<0.11
1,1,2-Trichloroethane	<0.25	<0.17	<0.18	<0.17	<0.18	<0.18	<0.18	<0.19	<0.19	<0.2
Trichloroethene (TCE)	<0.25	<0.17	<0.18	<0.17	<0.18	<0.18	<0.18	<0.19	**12**	**16**
Trichlorofluoromethane	**3.2**	<0.14	<0.15	**1.2**	**1.2**	<0.14	**1.6**	**2**	**2.6**	**2.6**
Trichlorotrifluoroethane	**120**	**1.8**	**4.9**	**6.5**	**7**	**6.5**	**11**	**16**	**51**	**39**
Vinyl Chloride	<0.34	<0.24	<0.25	<0.24	<0.25	<0.25	<0.25	<0.26	<0.26	<0.28

NOTES:
1. Sample locations are presented on Figure D.1.
2. Samples were collected in 1L Summa canisters back filled with 600 ml nitrogen, and were analyzed by Columbia Analytical Services, Simi Valley, California by method TO-15.
3. Detected analytes are presented in bold type.
4. < = Not detected at the detection limit shown.

GROUNDWATER SERVICES, INC.

TABLE D.12
RESULTS OF TO-15 ANALYSES
ESTCP: Vapor Intrusion Study

Altus Air Force Base, Altus, Oklahoma

SAMPLE LOCATION:	MW-4	MW-6	MW-8	MW-11	MW-12	SS-1	SS-2	SS-3
SAMPLE TYPE:	Headspace	Headspace	Headspace	Headspace	Headspace	Sub Slab	Sub Slab	Sub Slab
SAMPLE DATE:	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006	12/19/2006
NG/SCREEN DEPTH (ft bgs):	3.5-4.5	5.5-6.5	3.5-4.5	5.5-6.5	3.5-4.5	0.5	0.5	0.5
COMPOUND	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3	ug/m3
Compounds of Interest								
Chloromethane	<0.22	**19**	<0.14	<0.13	<0.13	<0.14	<0.14	<0.15
Vinyl Chloride	<0.4	<0.25	<0.25	<0.25	<0.25	<0.25	<0.26	<0.27
Bromomethane	<1	**22**	<0.65	<0.64	<0.64	<0.66	<0.66	<0.69
Chloroethane	<0.44	**7**	<0.27	<0.27	<0.27	<0.28	<0.28	<0.29
Acetone	**140**	**330**	**100**	**74**	**98**	**58**	**86**	**94**
Trichlorofluoromethane	<0.24	**1.6**	<0.15	<0.15	<0.15	**20**	**21**	**1.8**
1,1-Dichloroethene	<0.24	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.16
Methylene chloride	<0.4	<0.25	<0.25	<0.25	<0.25	<0.25	<0.26	<0.27
Trichlorotrifluoroethane	**76**	**59**	**6.3**	**4.2**	**2.3**	**540**	**590**	**6**
Carbon Disulfide	**3.4**	**3.2**	<0.27	**2.1**	<0.27	**3.7**	**1.9**	**10**
trans-1,2-Dichloroethene	<0.38	<0.24	<0.24	<0.23	<0.23	<0.24	<0.24	<0.25
1,1-Dichloroethane	<0.26	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.17
Methyl tert-Butyl Ether	<0.42	<0.26	<0.26	<0.26	<0.26	<0.26	<0.27	<0.28
2-Butanone (MEK)	**46**	**66**	**9.5**	**10**	**17**	**17**	**23**	**26**
cis-1,2-Dichloroethene	<0.27	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.18
Chloroform	<0.37	**3.5**	<0.23	<0.22	<0.22	<0.23	<0.23	<0.24
1,2-Dichloroethane	<0.33	<0.2	<0.2	<0.2	<0.2	<0.21	<0.21	<0.22
1,1,1-Trichloroethane	<0.17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.11	<0.11
Benzene	**3.1**	**1.2**	**1.1**	**1.3**	<0.19	<0.2	<0.2	<0.21
Carbon Tetrachloride	<0.29	<0.18	<0.18	<0.18	<0.18	<0.18	<0.19	<0.19
1,2-Dichloropropane	<0.26	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.17
Bromodichloromethane	<0.24	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.16
Trichloroethene	**5.9**	**560**	<0.18	**12**	**10**	**29**	**33**	**1.8**
cis-1,3-Dichloropropene	<0.31	<0.19	<0.19	<0.19	<0.19	<0.2	<0.2	<0.21
4-Methyl-2-pentanone	<0.2	**8.3**	<0.12	<0.12	<0.12	<0.13	<0.13	<0.13
trans-1,3-Dichloropropene	<0.22	<0.13	<0.14	<0.13	<0.13	<0.14	<0.14	<0.15
1,1,2-Trichloroethane	<0.29	<0.18	<0.18	<0.18	<0.18	<0.18	<0.19	<0.19
Toluene	**12**	**1.3**	<0.24	**1.9**	<0.23	<0.24	<0.24	**1.4**
2-Hexanone	**16**	**7.6**	**4**	**1.5**	**6.6**	**3.3**	**5.7**	**10**
Dibromochloromethane	<0.38	<0.24	<0.24	<0.23	<0.23	<0.24	<0.24	<0.25
1,2-Dibromoethane	<0.46	<0.28	<0.28	<0.28	<0.28	<0.29	<0.29	<0.3
Tetrachloroethene	**81**	**120**	**38**	**25**	**43**	**480**	**540**	**33**
Chlorobenzene	<0.46	<0.28	<0.28	<0.28	<0.28	<0.29	<0.29	<0.3
Ethylbenzene	<0.4	<0.25	<0.25	<0.25	<0.25	<0.25	<0.26	<0.27
m,p-Xylenes	**34**	<0.52	<0.52	<0.51	<0.51	<0.53	<0.54	<0.56
Bromoform	<0.51	<0.31	<0.32	<0.31	<0.31	<0.32	<0.33	<0.34
Styrene	<0.31	<0.19	<0.19	<0.19	<0.19	<0.2	<0.2	<0.21
o-Xylene	**14**	<0.29	<0.29	<0.29	<0.29	<0.3	<0.3	<0.32
1,1,2,2-Tetrachloroethane	<0.44	<0.27	<0.27	<0.27	<0.27	<0.28	<0.28	<0.29
1,3-Dichlorobenzene	<0.48	<0.29	<0.29	<0.29	<0.29	<0.3	<0.3	<0.32
1,4-Dichlorobenzene	<0.42	<0.26	<0.26	<0.26	<0.26	<0.26	<0.27	<0.28
1,2-Dichlorobenzene	<0.51	<0.31	<0.32	<0.31	<0.31	<0.32	<0.33	<0.34

NOTES:
1. Sample locations are presented on Figure D.1.
2. Samples were collected in 1L Summa canisters back filled with 600 ml nitrogen, and were analyzed by Columbia Analytical Services, Simi Valley, California by method TO-15.
3. Detected analytes are presented in bold type.
4. < = Not detected at the detection limit shown.

GROUNDWATER SERVICES, INC.

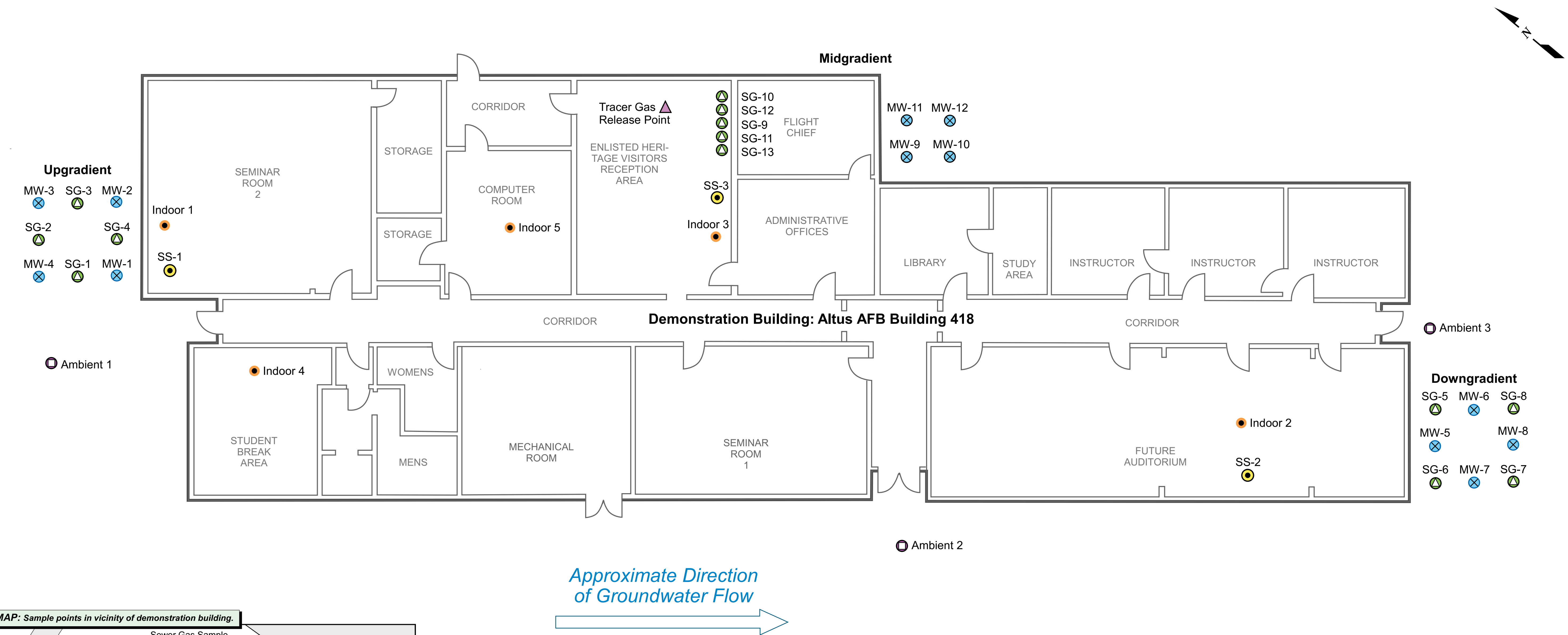
TABLE D.13
RESULTS OF SOIL PERMEABILITY TESTING

ESTCP: Vapor Intrusion Study
Altus Air Force Base, Altus, Oklahoma

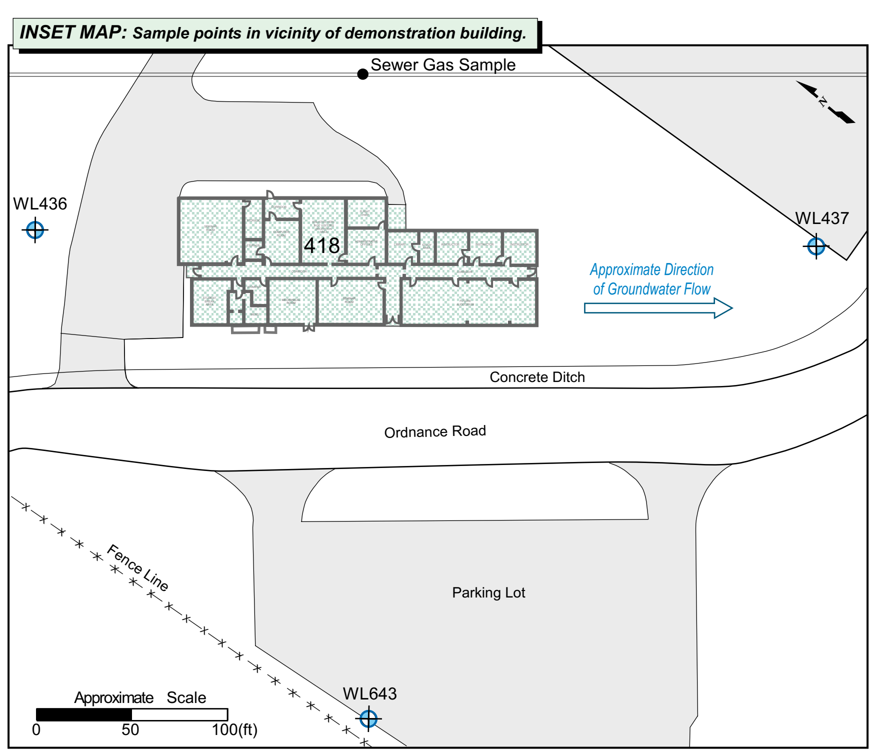
Cluster Location	Sample Point	Air Flow Rate (Q)		Vacuum (P)		Slope of Q vs. P	Permeability (cm2)
		(L/min)	(cc/min)	(in. Hg)	(in. H2O)		
Upgradient	SG-4	0.35	350	4	54.4	1.7455053	1.19E-10
		0.5	500	10.5	142.8		
		0.6	600	14.5	197.2		
	MW-4	1	1000	5	68	2.4108004	1.64E-10
		1.2	1200	9	122.4		
		1.3	1300	14	190.4		
Midgradient	MW-11	3	3000	0.147	2	547.61905	9.81E-09
		5	5000	0.37	5		
		8	8000	0.81	11		
Downgradient	SG-8	1.5	1500	0.15	2	445.53687	3.04E-08
		2.5	2500	0.29	4		
		3.3	3300	0.44	6		
		3.7	3700	0.59	8		
		5	5000	0.81	11		
		8	8000	1.18	16		
	SG-6	3.6	3600	0.15	2	734.88372	5.01E-08
		5	5000	0.22	3		
		9	9000	0.66	9		
	MW-8	3.2	3200	0.15	2	820	1.47E-08
		5	5000	0.29	4		
		7	7000	0.44	6		
		8	8000	0.59	8		
	MW-6	1	1000	0.22	3	143.83202	2.58E-09
		1.8	1800	0.44	6		
		2.7	2700	1	11		
		3.6	3600	1.25	17		
		5	5000	2.21	30		

Parameter Values for Soil Permeability Calculations

Parameter	Symbol	Value	Units	Basis
Viscosity of air	viscosity	1.73E-04	g/cm-s (poise)	Literature (40 deg. F)
Length: Soil gas pt	L	5.08	cm	Screen length for soil gas points (2 inches)
Length: Mont. Well	L	30.48	cm	Screen length for monitoring well points (12 inches)
Diameter: Soil Gas	D	1.6	cm	Inside diameter for soil gas points
Diameter: Mont. Well	D	3.2	cm	Inside diameter for monitoring well points
Units Conversion		1.07E-06		From calculation methods sheet
L/D Term: Soil Gas		0.368579		Calculated (=L/D)
L/D Term: Well Pt		0.096779		Calculated (=L/D)



INSET MAP: Sample points in vicinity of demonstration building.



Approximate Scale
0 7.5 15(ft)

LEGEND

- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port
- Existing 2" monitoring well screened in the upper water-bearing unit.

GROUNDWATER SERVICES, INC.

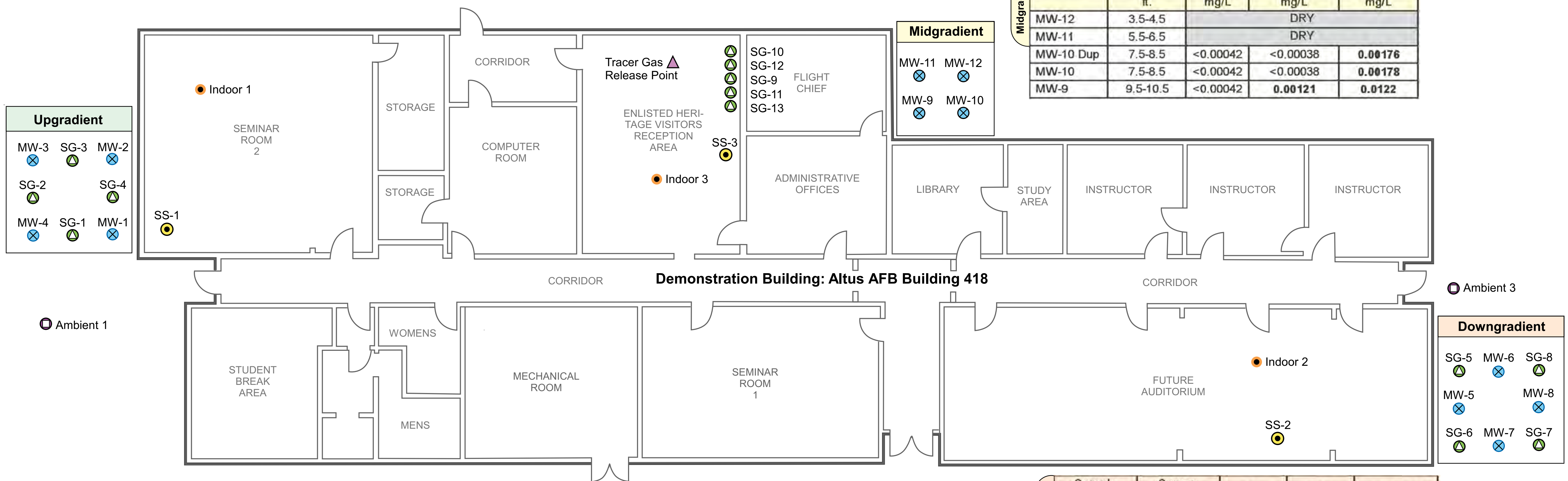
Sampling Locations

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	————	Appv'd By:	TEM
Scale:	As Shown	FIGURE D.1	

Upgradient Sample Location	Screen Interval	PCE	TCE	cis-1,2-DCE
	ft.	mg/L	mg/L	mg/L
MW-4	3.5-4.5	DRY		
MW-3	5.5-6.5	<0.00042	**0.00139**	<0.00038
MW-2	7.5-8.5	**0.00263**	**0.0112**	**0.00108**
MW-1	9.5-10.5	**0.00107**	**0.00579**	<0.00038

Midgradient Sample Location	Screen Interval	PCE	TCE	cis-1,2-DCE
	ft.	mg/L	mg/L	mg/L
MW-12	3.5-4.5	DRY		
MW-11	5.5-6.5	DRY		
MW-10 Dup	7.5-8.5	<0.00042	<0.00038	**0.00176**
MW-10	7.5-8.5	<0.00042	<0.00038	**0.00178**
MW-9	9.5-10.5	<0.00042	**0.00121**	**0.0122**



Downgradient Sample Location	Screen Interval	PCE	TCE	cis-1,2-DCE
	ft.	mg/L	mg/L	mg/L
MW-8	3.5-4.5	DRY		
MW-6	5.5-6.5	DRY		
MW-7	7.5-8.5	**0.00205**	**0.0352**	**0.00906**
MW-5 Dup	9.5-10.5	**0.00525**	**0.108**	**0.02**
MW-5	9.5-10.5	**0.00638**	**0.105**	**0.0186**

Approximate Direction of Groundwater Flow

INSET MAP: Sample points in vicinity of demonstration building.

WL436

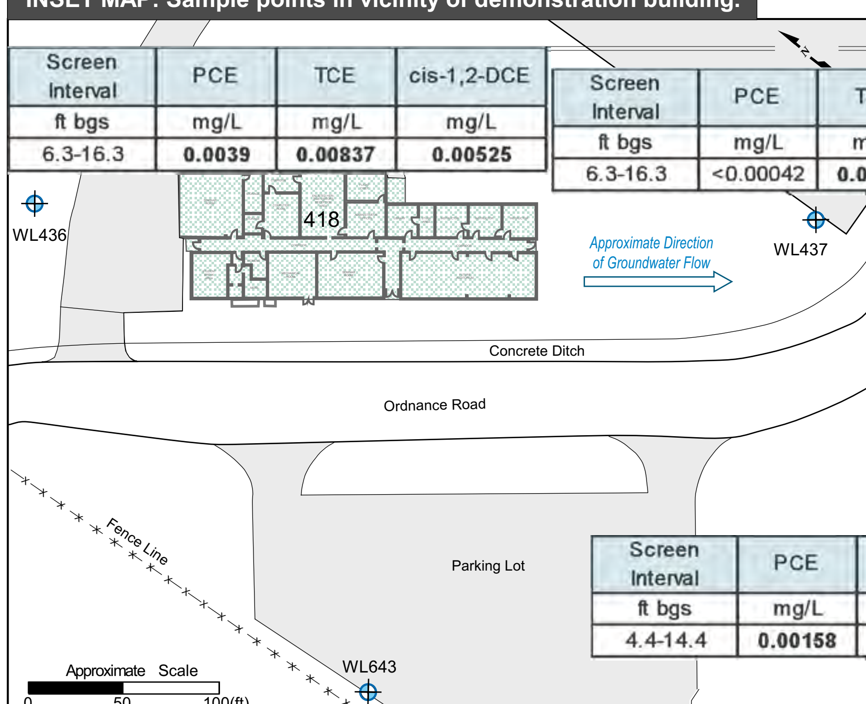
Screen Interval	PCE	TCE	cis-1,2-DCE
ft bgs	mg/L	mg/L	mg/L
6.3-16.3	**0.0039**	**0.00837**	**0.00525**

WL437

Screen Interval	PCE	TCE	cis-1,2-DCE
ft bgs	mg/L	mg/L	mg/L
6.3-16.3	<0.00042	**0.00266**	<0.00038

WL643

Screen Interval	PCE	TCE	cis-1,2-DCE
ft bgs	mg/L	mg/L	mg/L
4.4-14.4	**0.00158**	**0.00698**	<0.00038



Approximate Scale
0 7.5 15(ft)

LEGEND

- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port
- Existing 2" monitoring well screened in the upper water-bearing unit.

GROUNDWATER SERVICES, INC.

Results of Groundwater Sampling and Analysis

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

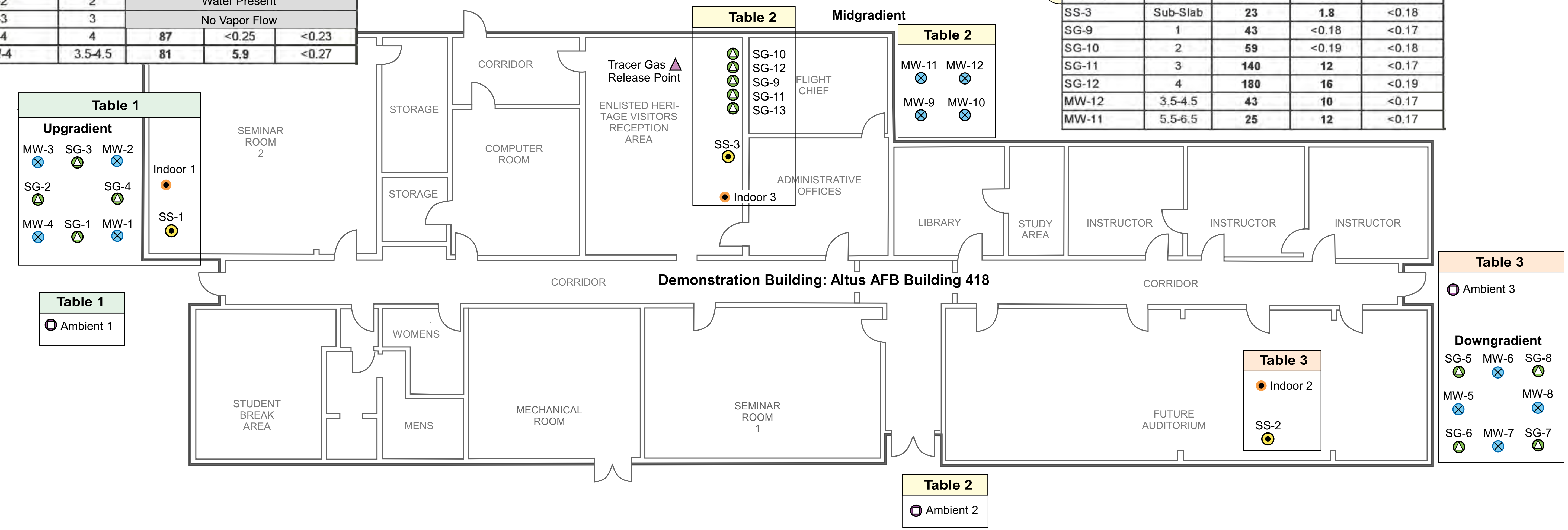
GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:		Appv'd By:	TEM
Scale:	As Shown		FIGURE D.2

Table 1

Sample Location	Depth / Location	PCE	TCE	cis-1,2-DCE
	ft.	ug/m3	ug/m3	ug/m3
Ambient 1	Ambient	**0.14**	**0.047**	<0.005
Indoor 1	Indoor	**0.36**	**0.1**	<0.0044
SS-1	Sub-Slab	**480**	**29**	<0.17
SG-1	1	Water Present		
SG-2	2	Water Present		
SG-3	3	No Vapor Flow		
SG-4	4	**87**	<0.25	<0.23
MW-4	3.5-4.5	**81**	**5.9**	<0.27

Table 2

Sample Location	Depth / Location	PCE	TCE	cis-1,2-DCE
	ft.	ug/m3	ug/m3	ug/m3
Ambient 2	Ambient	**0.15**	**0.056**	<0.0046
Indoor 3	Indoor	**0.28**	**0.12**	<0.0057
SS-3	Sub-Slab	**23**	**1.8**	<0.18
SG-9	1	**43**	<0.18	<0.17
SG-10	2	**59**	<0.19	<0.18
SG-11	3	**140**	**12**	<0.17
SG-12	4	**180**	**16**	<0.19
MW-12	3.5-4.5	**43**	**10**	<0.17
MW-11	5.5-6.5	**25**	**12**	<0.17



Approximate Direction of Groundwater Flow

Table 3

Sample Location	Depth / Location	PCE	TCE	cis-1,2-DCE
	ft.	ug/m3	ug/m3	ug/m3
Ambient 3	Ambient	**0.21**	**0.087**	<0.004
Indoor 2	Indoor	**0.59**	**0.18**	<0.0049
Indoor 2 Dup	Indoor	**0.63**	**0.18**	<0.0052
SS-2	Sub-Slab	**540**	**33**	<0.17
SG-5	1	**4.1**	<0.17	<0.16
SG-6	2	**19**	<0.18	<0.17
SG-7	3	**33**	<0.17	<0.16
SG-8	4	**40**	<0.18	<0.17
SG-8 Dup	4	**34**	<0.18	<0.17
MW-8	3.5-4.5	**38**	<0.18	<0.17
MW-6	5.5-6.5	**120**	**560**	<0.17

LEGEND

- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port

Approximate Scale

0 7.5 15(ft)

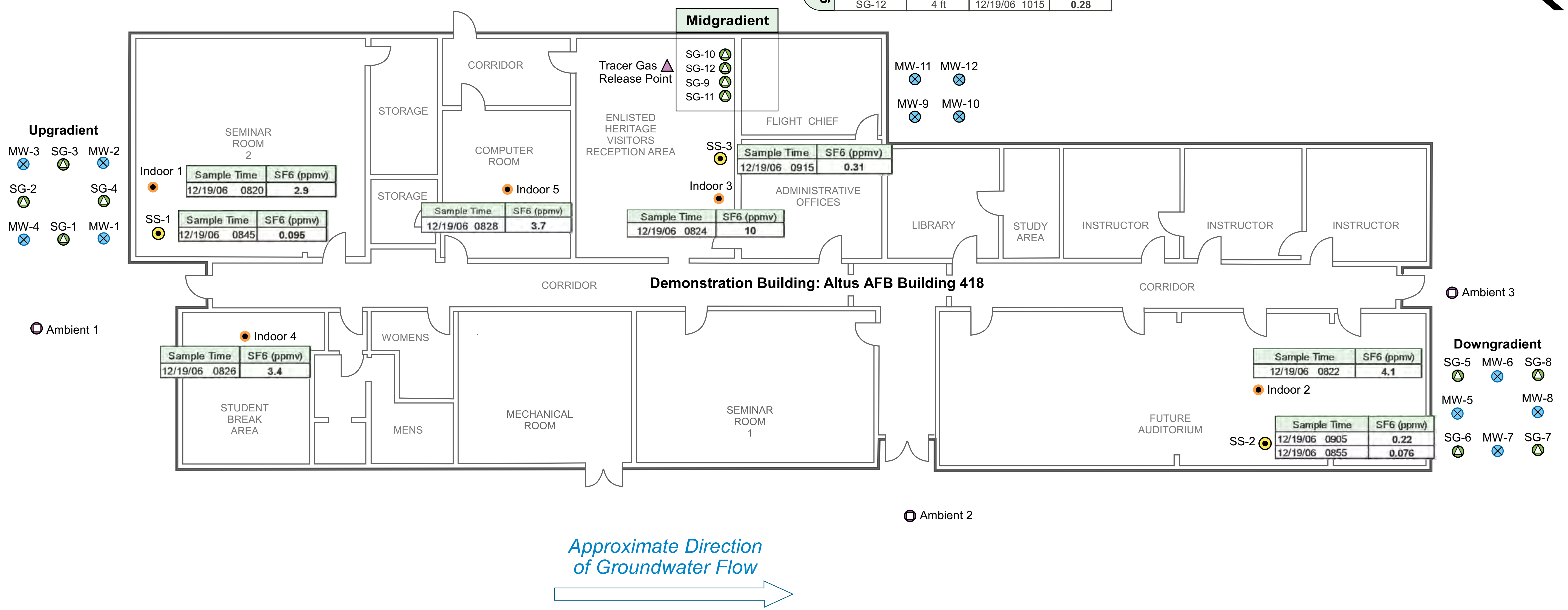
GROUNDWATER SERVICES, INC.

Gas Sampling and Analysis Results (Ambient, Indoor, Sub-Slab, Soil Gas, Well Headspace)

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	________	Appv'd By:	TEM
Scale:	As Shown		**FIGURE D.3**

Mid-gradient Sample ID	Depth	Sample Time	SF6 (ppmv)
SG-9	1 ft	12/19/06 1001	**0.71**
SG-10	2 ft	12/19/06 1007	**0.2**
SG-11	3 ft	12/19/06 1010	**0.12**
SG-12	4 ft	12/19/06 1015	**0.28**



Note: Sample date = 7/11/06

LEGEND

- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port
- Existing 2" monitoring well screened in the upper water-bearing unit.

Approximate Scale

0 7.5 15(ft)

GROUNDWATER SERVICES, INC.

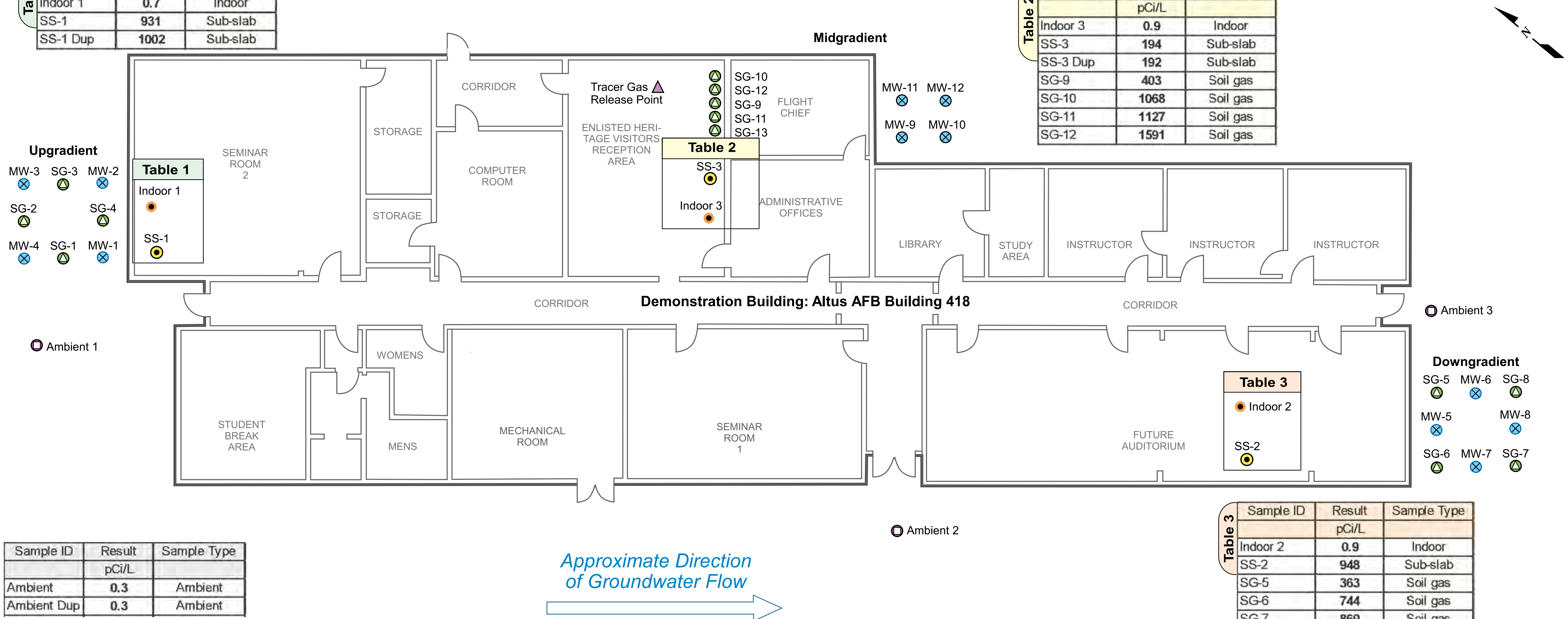
Results of SF_6 Tracer Gas Sampling and Analysis

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No: G-2882		Drawn By: CRW	
Issued: 2/_/07		Chk'd By: TNN	
Revised: ______		Appv'd By: TEM	
Scale: As Shown		FIGURE D.4	

Table 1 Sample ID	Result	Sample Type
	pCi/L	
Indoor 1	**0.7**	Indoor
SS-1	**931**	Sub-slab
SS-1 Dup	**1002**	Sub-slab

Table 2 Sample ID	Result	Sample Type
	pCi/L	
Indoor 3	**0.9**	Indoor
SS-3	**194**	Sub-slab
SS-3 Dup	**192**	Sub-slab
SG-9	**403**	Soil gas
SG-10	**1068**	Soil gas
SG-11	**1127**	Soil gas
SG-12	**1591**	Soil gas



Sample ID	Result	Sample Type
	pCi/L	
Ambient	**0.3**	Ambient
Ambient Dup	**0.3**	Ambient

Table 3 Sample ID	Result	Sample Type
	pCi/L	
Indoor 2	**0.9**	Indoor
SS-2	**948**	Sub-slab
SG-5	**363**	Soil gas
SG-6	**744**	Soil gas
SG-7	**869**	Soil gas
SG-8	**881**	Soil gas

Approximate Scale

0 7.5 15(ft)

LEGEND

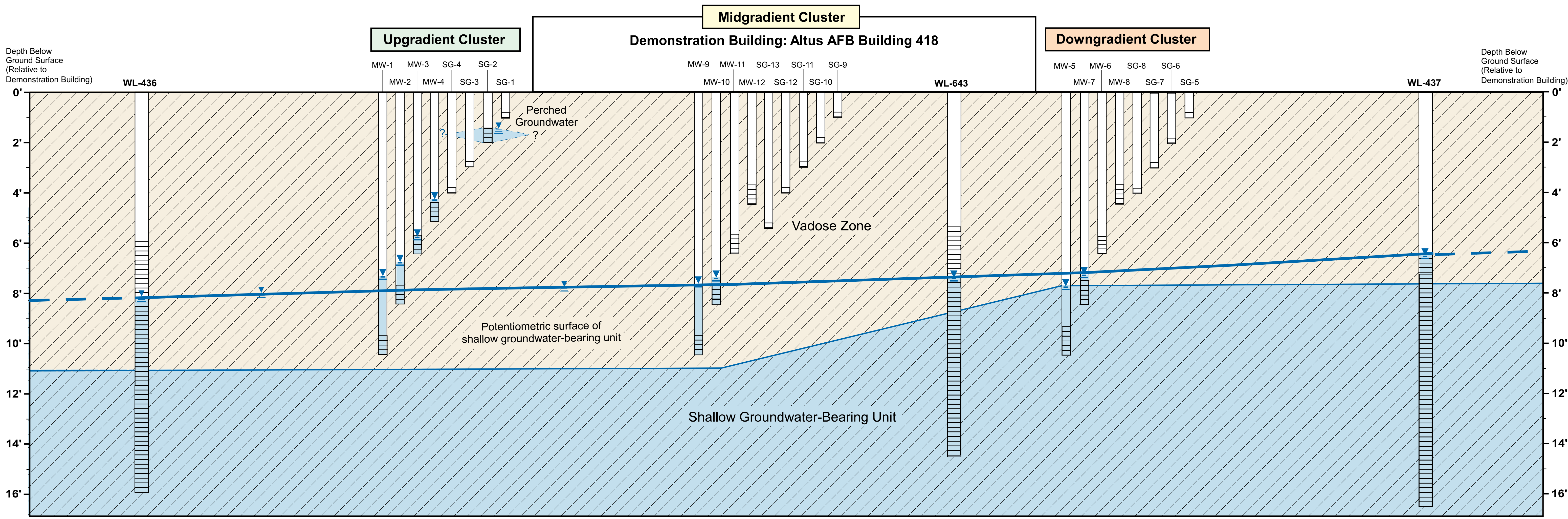
- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port
- Existing 2" monitoring well screened in the upper water-bearing unit.

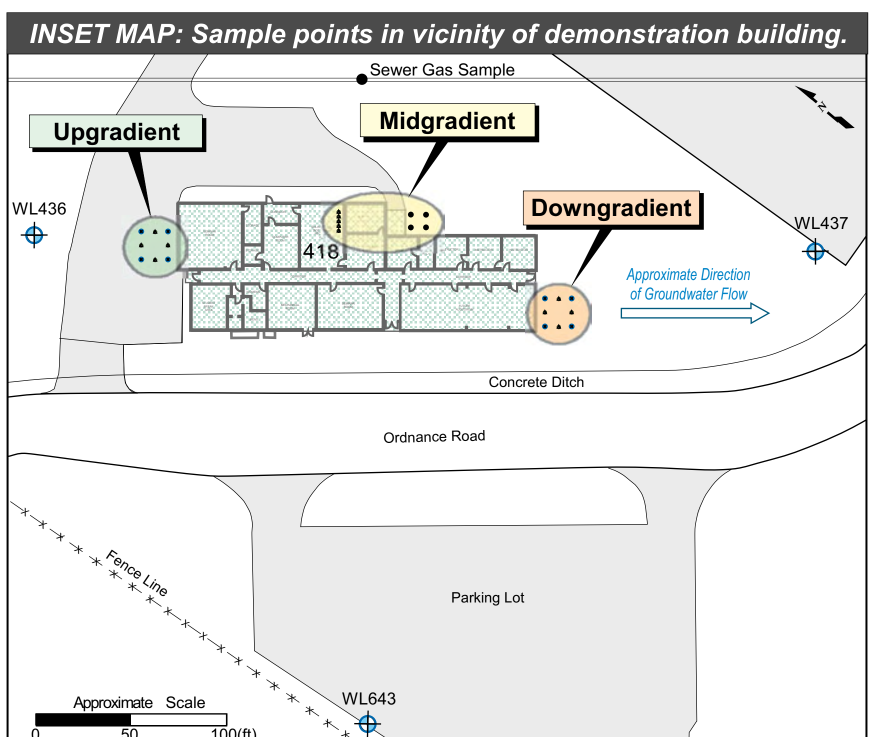
GROUNDWATER SERVICES, INC.

Results of Radon Sampling and Analysis

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No: G-2882		Drawn By: CRW	
Issued: 3/2/07		Chk'd By: TNN	
Revised:		Appv'd By: TEM	
Scale: As Shown		**FIGURE D.5**	





LEGEND

- Static water level measured on 12/19/06
- Screen Interval
- Silty Clay Soil Type

GROUNDWATER SERVICES, INC.

Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	———	Appv'd By:	TEM
Scale:	Not to Scale		FIGURE D.6

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix E

Example Calculations

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

E.1 ATTENUATION FACTORS

Calculation E.1.1A: Sub Slab to Indoor Air Attenuation Factor (No Correction for Ambient Air Concentration)

$$AF_{SS-IA} = \frac{C_{IA}}{C_{SS}}$$

Where:

AF_{SS-IA} = Sub-slab to indoor air attenuation factor (unitless)
C_{IA} = Average radon or TCE concentration in indoor air
(Average from Table 8 for radon ; Table 6 for TCE, PCE)
C_{SS} = Average radon concentration in sub-slab,
(Average from Table 8 for radon ; Table 5 for TCE, PCE)

Example Calculation: Slab Attenuation Factor Using Radon Data

$$AF_{SS-IA} = \frac{0.83}{702}$$

$AF_{SS-IA} = 1.2 \times 10^{-3}$

Calculation Results: Sub-slab to Indoor Air Attenuation Factor

Compound	Average Sub-Slab Conc. (pCi/L)	Average Indoor Conc. (pCi/L)	Attenuation Factor
Radon	702	0.83	0.0012
TCE	21	0.13	0.0062
PCE	348	0.42	0.0012

Note: For average concentration, all detected values were averaged for each location, then location concentrations averaged to calculate overall average indoor or sub-slab concentration.

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.1.1B: Sub Slab to Indoor Air Attenuation Factor (Corrected for Ambient Air Concentration)

$$AF_{SS-IA} = \frac{C_{IA} - C_{AA}}{C_{SS}}$$

Where:

$AF_{SS\text{-}IA}$ = Sub-slab to indoor air attenuation factor (unitless)
C_{IA} = Average radon or TCE concentration in indoor air
(Average from Table 8 for radon; Table 6 for TCE, PCE)
C_{AA} = Average radon or TCE concentration in ambient air
(Average from Table 8 for radon; Table 6 for TCE, PCE)
C_{SS} = Average radon concentration in sub-slab,
(Average from Table 8 for radon; Table 5 for TCE, PCE)

Example Calculation: Slab Attenuation Factor Using Radon Data

$$AF_{SS-IA} = \frac{0.83 - 0.30}{702}$$

$AF_{SS\text{-}IA} = 7.6 \times 10^{-4}$

Calculation Results: Sub-slab to Indoor Air Attenuation Factor

Compound	Average Sub-Slab Conc. (pCi/L or ug/m#)	Average Indoor Conc. (pCi/L or ug/m#)	Average Ambient Conc. (pCi/L or ug/m#)	Attenuation Factor
Radon	702	0.83	0.3	0.00076
TCE	21	0.13	0.063	0.0033
PCE	348	0.42	0.17	0.00072

Note: For average concentration, all detected values were averaged for each location, then location concentrations averaged to calculate overall average indoor or sub-slab concentration.
NC = Not calculated because ambient TCE concentration greater than indoor TCE concentration.

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.1.2: Estimated Indoor Air VOC Concentrations Due to Sub-Slab Vapor Intrusion

$$C_{IA} = C_{SS} \times AF_{SS-IA}$$

Where:

C_{IA} = Estimated VOC concentration in indoor air due to vapor intrusion (ug/m^3)
C_{SS} = Average VOC concentration in sub-slab, (ug/m^3, average value from Table 5, TO-15 results)
AF_{SS-IA} = Sub-slab to indoor air attenuation factor for radon (Uncorrected: 1.2 x 10^{-3}; Corrected for ambient: 7.6 x 10^{-4})

Example Calculation: Estimated indoor TCE concentration

C_{ss} = 21 ug/m^3, average of sub-slab TCE measurements by TO-15 from Table 5

$$C_{IA} = 21 \text{ ug/m}^3 \times 1.2 \times 10^{-3}$$

$$C_{IA} = 0.025 \text{ ug/m}^3$$

Calculation Results: Estimated VOC Concentration in Indoor Air from Vapor Intrusion

Compound	Average Sub-Slab Conc. (ug/m^3)	Estimated Indoor Conc. due to VI (ug/m^3)	Measured Indoor Conc. (ug/m^3)
Using Radon AF Not Corrected for Ambient			
TCE	21	0.025	0.13
PCE	348	0.41	0.42
Using Radon AF Corrected for Ambient			
TCE	21	0.016	0.13
PCE	348	0.26	0.42

Note: Measured indoor TCE concentration is average from Table 6.

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.1.3: Deep Soil Gas to Indoor Air Attenuation Factor

$$AF_{SG-IA} = \frac{C_{IA}}{C_{SG}}$$

Where:

AF_{SG-IA} = Deep soil gas to indoor air attenuation factor (unitless)
C_{SG} = VOC concentration in shallowest measured well headspace sample (ug/m^3, average, Table 4)
C_{IA} = VOC concentration in Indoor Air from Vapor Intrusion (ug/m3, see Calc. D.1.2)

Example Calculation: Deep Soil Gas to Indoor Air Attenuation Factor For TCE

C_{SG} = 5.5 ug/m^3

$$AF_{SG-IA} = \frac{0.025}{5.5}$$

AF_{SG-IA}= 3.0 x 10^{-3}

Calculation Results: Deep Soil Gas to Indoor Air AF

Compound	Average Deep SG Conc. (ug/m^3)	Deep SG to IA AF
Using Radon AF Corrected for Ambient		
TCE	5.4	3.0 x 10^{-3}
PCE	54	4.9 x 10^{-3}

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.1.4 Groundwater to Indoor Air Attenuation Factor

$$AF_{GW-IA} = \frac{C_{IA}}{C_{Gw} x H'}$$

Where:

AF_{GW-IA}	=	Groundwater to indoor air attenuation factor (unitless)
C_{IA}	=	VOC concentration in Indoor Air (ug/m3, see Calc. D.1.2)
C_{GW}	=	VOC concentration in Groundwater (average of shallowest water samples, see Fig. 6)
H'	=	Henry's Law constant (0.765 PCE; 0.428 TCE, http://www.tnrcc.state.tx.us/permitting/trrp.htm)

Example Calculation: Groundwater to Indoor Air Attenuation Factor for TCE

$$AF_{GW-IA} = \frac{0.016}{12{,}300 x 0.428}$$

$$AF_{GW-IA} = 3.1 \text{ x } 10^{-6}$$

Calculation Results: Groundwater to Indoor Air AF

Compound	Groundwater Conc. (ug/m^3)	GW to IA AF
Using Radon AF Corrected for Ambient Radon Conc.		
TCE	12,300	3.1 x 10^{-6}
PCE	963	3.6 x 10^{-4}

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

E.2 MASS FLUX

Calculation E.2.1: Lateral Mass Flux in Shallow Groundwater Under Demonstration Building

$$F_{GW} = C_{GW} \times A \times q$$

Where

F_{GW} = Lateral mass flux through shallow groundwater under demonstration building (ug/day)

C_{GW} = Concentration of constituent in groundwater (ug/ft^3, from upgradient well WL-436, see Fig. 6)

A = Area through which flux is occurring (57 ft x 2 ft = 114 ft^2, width of building in direction of GW flow x 2 ft depth)

q = Darcy velocity = k x i = (0.076 ft/day)

k = Hydraulic conductivity (8.0 x 10^{-3} ft/min, average hydraulic conductivity measured at the nearest 2 wells: WL139 & WL-315, RFI report for Altus AFB)

i = Hydraulic gradient (0.0066, average value in vicinity of demonstration building, RFI report for Altus AFB, Figure 4.5-2)

Example Calculation: Mass flux of PCE in groundwater

C_{GW} = 3.9 ug/L (from upgradient well WL-436, see Fig. 6) = 110 ug/ft^3

F_{GW} = 110 ug/ft^3 x 114 ft^2 x 0.076 ft/day

F_{GW} = 956 ug/day

Calculation Results: Lateral mass flux in shallow groundwater

Compound	Groundwater Conc. (ug/ft^3)	GW Mass Flux (ug/day)
Perchloroethene (PCE)	110	960
Trichloroethene (TCE)	240	2,100
cis-1,2-Dichloroethene	150	1,300

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.2.2: Vertical Mass Flux Across Groundwater-Soil Gas Interface

$$F_{GW-SG} = D^{eff} \times \frac{\Delta C}{\Delta X} \times A$$

$$D^{eff} = D^{wat} \times \theta_T^{1.33}$$

Where

$F_{GW\text{-}SG}$	=	Vertical mass flux across the groundwater-soil gas interface under demonstration building (ug/day)
D^{wat}	=	Diffusivity in water (ft^2/day, TCE: 8.5 x 10^{-4}, PCE: 8.0 x 10^{-4}, 1,2-DCE: 1.05 x 10^{-3})
θ_T	=	Total porosity in soil (0.389, average from Table 1)
D^{eff}	=	Effective diffusion coefficient (ft^2/day, calculated – chemical-specific)
ΔC	=	Difference in VOC concentration between deeper groundwater and shallower groundwater (ug/m3)
ΔX	=	Depth from deeper groundwater to shallower groundwater (ft)
A	=	Area building foundation (8,963 ft^2, Bldg. 418)

Vertical concentration gradient in groundwater

Well Pair	**ΔC (ug/L)**	**ΔX (ft)**	**Concentration Gradient (ug/L-ft)**
PCE			
MW-1, MW-3	0.65	4	0.16
MW-9, MW-10	N/A	2	N/A
MW-5, MW-7	3.77	2	1.89
		Average Gradient for PCE:	**1.02**
TCE			
MW-1, MW-3	4.4	4	1.10
MW-9, MW-10	0.83	2	0.42
MW-5, MW-7	71.3	2	35.65
		Average Gradient for TCE:	**12.39**
1,2-DCE			
MW-1, MW-3	N/A	4	N/A
MW-9, MW-10	10.4	2	5.20
MW-5, MW-7	8.4	2	4.20
		Average Gradient for TCE:	**4.70**

N/A = Not applicable, PCE not detected in either well

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Example Calculation: Mass flux of TCE across groundwater-soil gas interface

D^{wat} = Diffusivity in water (TCE = $8.5\text{x}10^{-4}$ ft^2/day)
D^{eff} = $8.5\text{x}10^{-4}$ ft^2/day x $0.389^{1.33}$ = 2.4 x 10^{-4} ft^2/day

$\Delta C/\Delta X$ = 12.39 ug/L - ft (average value for TCE)

$F_{GW\text{-}SG}$ = $2.4\text{x}10^{-4}$ ft^2/day x (12.39 ug/L- ft) x 8963 ft^2 x (1 m^3 / 35.3 ft^3) x 1000 L/m^3)

$F_{GW\text{-}SG}$ = 760 ug/day

Vertical mass flux of TCE across groundwater-soil gas interface

Residence	$\Delta C/\Delta X$ (ug/L-ft)	**Mass Flux Across Interface (ug/day)**
PCE	1.02	59
TCE	12.39	760
1,2-DCE	4.7	360

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.2.3: Vertical Mass Flux in Soil Column Under Demonstration Building

$$F_{SG} = D^{eff} \times \frac{\Delta C}{\Delta X} \times A$$

$$D^{eff} = D^{air} \frac{\theta_{as}^{3.33}}{\theta_T^2} + \left[\frac{D^{wat}}{H'}\right] \times \left[\frac{\theta_{ws}^{3.33}}{\theta_T^2}\right]$$

Where

F_{SG}	=	Vertical mass flux through soil column under demonstration building (ug/day)
D^{eff}	=	Effective diffusion coefficient (ft^2/day, calculated – chemical-specific)
ΔC	=	Difference in VOC concentration between deep soil gas and sub-slab (ug/m3)
ΔX	=	Depth from deep soil gas VOC concentration measurement and sub-slab (ft)
A	=	Area building foundation (8,963 ft^2, Bldg. 418)
D^{air}	=	Diffusivity in air (ft^2/day, chemical-specific)
D^{wat}	=	Diffusivity in water (ft^2/day, chemical-specific)
θ_{as}	=	Air filled porosity in soil (0.115, average from Table 1)
θ_{ws}	=	Water filled porosity in soil (0.273, average from Table 1)
θ_T	=	Total porosity in soil (0.389, average from Table 1)
H'	=	Henry's Law constant (chemical-specific)

Effective Diffusivities

Compound	H'	D^{air} (ft^2/day)	D^{water} (ft^2/day)	D^{eff} (ft^2/day)
Perchloroethene (PCE)	0.765	6.72	8.0×10^{-4}	0.0331
Trichloroethene (TCE)	0.428	7.37	8.5×10^{-4}	0.0363
cis-1,2-Dichloroethene	0.187	6.84	1.1×10^{-3}	0.0342

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Example Calculation: Mass Flux of PCE in soil gas (based on gradient from midgradient cluster)

D^{eff} = Effective diffusion coefficient (PCE = 0.0331 ft^2/day)

ΔC = 63 ug/m^3 (average value at deepest MW headspace sample at each cluster, see Table 3) – 348 ug/m^3 (average sub-slab, see Table 5) = -285 ug/m^3

ΔX = Difference between the depth of the soil gas sample and the ground surface (6ft – 0ft = 6 ft)

F_{SG} = 0.0331 ft^2/day x (-285 ug/m^3 ÷ 6 ft) x 8,963 ft^2 x (1 m^3 / 35.3 ft^3)

F_{SG} = -400 ug/day (Value not meaningful because sub-slab conc. > soil gas conc.)

Calculation Results: Vertical mass flux in soil column

Compound	ΔC (ug/m^3)	**ΔX (ft)**	**Soil Column Mass Flux (ug/day)**
Perchloroethene (PCE)	-285	6	NM
Trichloroethene (TCE)	173	6	242
cis-1,2-Dichloroethene	N/A	6	N/A

N/A = Not applicable, no 1,2-DCE detected in soil gas or sub-slab samples.

NM = Mass flux through soil column not meaningful because measured sub-slab concentration higher than measured soil gas concentration indicating negative concentration gradient.

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.2.4: Mass Flux Through Demonstration Building Foundation

$$F_{SS-IA} = C_{IA} \times V \times ER$$

Where

$F_{SS\text{-}IA}$ = Mass flux from sub-slab into building (ug/day)
C_{IA} = Steady-state concentration of constituent in indoor air (ug/m^3, from Calc. D.1.2)
V = Volume of demonstration building (89,625 ft^3 = 2,538 m^3)
ER = Building air exchange rate (1.5 day^{-1}, see Calc. D.3.1)

Example Calculation: Mass flux of PCE through building foundation

C_{IA} = 0.41 ug/m^3 (see Calc. D.1.2, uncorrected value)

$F_{SS\text{-}IA}$ = 0.41 ug/m^3 x 2,538 m^3 x 1.5 day^{-1}

$F_{SS\text{-}IA}$ = 1580 ug/day

Results: Mass flux through building foundation - No Ambient Correction

Compound	Indoor Air Conc. (ug/m^3)	SS to IA Mass Flux (ug/day)
Perchloroethene (PCE)	0.41	1580
Trichloroethene (TCE)	0.025	97
cis-1,2-Dichloroethene	<0.0002	<0.8

Results: Mass flux through building foundation - With Ambient Correction

Compound	Indoor Air Conc. (ug/m^3)	SS to IA Mass Flux (ug/day)
Perchloroethene (PCE)	0.26	1010
Trichloroethene (TCE)	0.016	62
cis-1,2-Dichloroethene	<0.0001	<0.5

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

E.3 STATISTICAL CALCULATIONS

Calculation E.3.1: Standard Deviation

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

Where:

S	=	Standard deviation of the sample set
N	=	Number of samples
x_{ii}	=	Value of the ith sample
$\overline{x}$	=	Sample mean

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

E.4 OTHER CALCULATIONS

Calculation E.4.1: Building Air Exchange Rate

$$\text{ER (day}^{-1}) = \frac{\text{Fresh Air Entry Rate (ft}^3\text{/day)}}{\text{Building Volume(ft}^3)}$$

$$\text{Fresh Air Entry Rate (ft}^3\text{/day)} = \frac{\text{Tracer Gas Release Rate (ft}^3\text{/day)}}{\text{Measured Tracer Gas Concentration (fraction)}}$$

Where:

ER = Building air exchange rate (day^{-1})
Fresh Air Entry Rate = Rate at which ambient air enters building (ft^3/day)
Tracer Gas Release Rate = Rate at which 100% SF_6 tracer gas was released during test
(12.8 mL SF_6/min = 0.65 ft^3 SF_6/day)
Measured Tracer Gas Concentration = 4.8 ppmv = 4.8 x 10^{-6}
(Avg of Tedlar grab sample, Table 7).

Building Volume = Volume of demonstration building (89,625 ft^3)

Example Calculation: Building Air Exchange Rate

$$\text{Fresh Air Entry Rate} = \frac{0.65\, ft^3/day}{4.8\times10^{-6}} = 135{,}000\ \text{ft}^3\text{/day}$$

ER = 135,000 ft^3/day / 89,625 ft^3 = 1.5 day^{-1}

Calculation Results: Building Air Exchange Rate

Test Building	Fresh Air Entry Rate (ft^3/day)	Air Exchange Rate (day^{-1})
Building 418	135,000	1.5

GROUNDWATER SERVICES, INC.

APPENDIX D: DATA EVALUATION CALCULATIONS

Calculation E.4.2: Line Volume for Subsurface Sample Collection Methods

$$\text{LV (mL/ft)} = \frac{1}{4}\pi d^2 \text{ x } 30.48\text{cm/ft}$$

Where:

LV = Line volume per foot of line length (mL/ft)
d = Line diameter (cm)

Example Calculation: Line volume of 1/8” Nylaflow tubing

d = 0.078” (Inside diameter) = 0.198 cm
LV = 0.25 x 3.14 x (0.198 cm)^2 x 30.48 cm/ft
LV = 0.94 mL/ft

Line volume for 1/8” Nylaflow tubing = 0.94 mL/ft

July 31, 2007

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix F

Statistical Evaluation

TABLE F.1
STATISTICAL ANALYSIS: SPATIAL VARIABILITY OF TCE AND PCE RESULTS

ESTCP: Vapor Intrusion Study

	TCE									PCE			
TEST SITE:	Altus Air Force Base				Hill Air Force Base					Altus Air Force Base			
TEST LOCATION:	Building 418				Residence 1			Residence 2		Building 418			
SAMPLE EVENT:	Event 1	Event 2	Event 3	Event 4	Event 1 8260	Event 1 TO-15	Event 2	Event 1 8260/TO-1	Event 2	Event 1	Event 2	Event 3	Event 4
SAMPLE DATE:	3/21/2001	3/22/2001	7/9/2002	12/18/2002	8/31/2001	8/31/2001	3/13/2002	8/28/2001	3/12/2002	3/21/2001	3/22/2001	7/9/2002	12/18/2002
Ambient Vapor Samples ug/m³													
Mean	<5	<5	12.300	0.063	NA	0.063	0.092	<0.045	<0.055	<5	<5	0.250	0.167
Standard Deviation	NC	NC	5.742	0.021	NA	0.027	0.085	NC	NC	NC	NC	0.235	0.038
Coefficient of Variation	NC	NC	0.467	0.331	NA	0.434	0.923	NC	NC	NC	NC	0.941	0.227
Indoor Air Vapor Samples ug/m³													
Mean	NC	NC	9.467	0.133	NA	0.060	0.075	0.062	0.140	NC	NC	0.260	0.417
Standard Deviation	NC	NC	2.214	0.042	NA	0.006	0.016	0.013	0.044	NC	NC	0.060	0.172
Coefficient of Variation	NC	NC	0.234	0.312	NA	0.097	0.218	0.213	0.311	NC	NC	0.231	0.413
Subslab Vapor Samples ug/m³													
Mean	19.0	21.7	49.8	21.3	16.7	20.3	8.4	15	<0.94	58.7	58.3	402	348
Standard Deviation	17.3	23.7	62.0	17.0	11.5	14.6	8.6	NC	NC	61.8	70.7	501	283
Coefficient of Variation	0.913	1.09	1.244	0.798	0.693	0.717	1.02	NC	NC	1.05	1.21	1.25	0.813
Soil Gas Samples ug/m³ Deepest Point													
Mean	NC	NC	NC	NC	49	158	NC	10.7	NC	36.3	23.3	78.3	101.3
Standard Deviation	NC	NC	NC	NC	53.5	253	NC	1.15	NC	50.8	28.3	45.7	72.6
Coefficient of Variation	NC	NC	NC	NC	1.09	1.6	NC	0.11	NC	1.40	1.212	0.584	0.716
Well Headspace Vapor Samples ug/m³ Shallowest Point													
Mean	70.7	47.7	38.7	5.36	44	52	41	88	197	13.7	13.3	157	54.0
Standard Deviation	63.6	71.3	37.9	4.93	38.6	50.7	28	114	297	15.0	5.77	63.5	23.5
Coefficient of Variation	0.90	1.50	0.98	0.92	0.88	0.98	0.68	1.30	1.51	1.10	0.43	0.41	0.44
Groundwater Samples mg/L Deepest Point													
Mean	0.0341	NC	0.0344	0.0373	0.0043	NC	0.0054	0.0066	0.0055	0.0065	NC	0.0024	0.0022
Standard Deviation	0.057	NC	0.044	0.059	0.001	NC	0.001	0.001	0.002	0.011	NC	0.002	0.003
Coefficient of Variation	1.67	NC	1.28	1.57	0.313	NC	0.133	0.087	0.325	1.67	NC	0.729	1.17
Groundwater Samples mg/L Shallowest Point													
Mean	0.0014	NC	0.0158	0.0123	0.0034	NC	0.0016	0.0017	0.0018	NC	NC	NC	NC
Standard Deviation	0.001	NC	0.024	0.020	0.003	NC	0.001	0.002	0.002	NC	NC	NC	NC
Coefficient of Variation	0.811	NC	1.503	1.608	0.929	NC	0.836	0.918	1.087	NC	NC	NC	NC

NOTES:
1. NA = Not Analyzed; NC = Not calculated for data sets with majority non-detect results.

GROUNDWATER SERVICES, INC.

TABLE F.2
STATISTICAL ANALYSIS: SPATIAL VARIABILITY OF RADON RESULTS

ESTCP: Vapor Intrusion Study

TEST SITE:	Altus Air Force Base			Hill Air Force Base			
TEST LOCATION:	Building 418			Residence 1		Residence 2	
SAMPLE EVENT:	Event 1	Event 3	Event 4	Event 1	Event 2	Event 1	Event 2
SAMPLE DATE:	3/21/2001	7/9/2002	12/18/2002	8/31/2001	3/13/2002	8/28/2001	3/12/2002
Ambient Vapor Samples ug/m³							
Mean	NA	0.13	0.30	NA	0.095	NC	NC
Standard Deviation	NA	NC	NC	NA	NC	NC	NC
Coefficient of Variation	NA	NC	NC	NA	NC	NC	NC
Indoor Air Vapor Samples ug/m³							
Mean	0.40	0.353	0.833	0.320	0.607	<0.375	0.797
Standard Deviation	NC	0.093	0.155	0.137	0.195	NC	0.006
Coefficient of Variation	NC	0.263	0.139	0.431	0.321	NC	0.007
Subslab Vapor Samples ug/m³							
Mean	843.0	573.0	702.0	450	67.7	409	427.000
Standard Deviation	322.0	42.0	441.0	NC	54.0	NC	283.000
Coefficient of Variation	0.381	0.073	0.628	NC	0.80	NC	0.662

NOTES:
1. NA = Not Analyzed; NC = Not calculated for data sets with less than three measurements or majority non-detect results.

GROUNDWATER SERVICES, INC.

ATTACHMENT F.3
STATISTICAL ANALYSIS: SHORT-TERM TEMPORAL VARIABILITY AT ALTUS AFB

ESTCP: Vapor Intrusion Study

	Perchloroethene				Trichloroethene				cis 1,2-Dichloroethene			
	Sampling Event 1	Sampling Event 2	Difference	Relative Percent Difference	Sampling Event 1	Sampling Event 2	Difference	Relative Percent Difference	Sampling Event 1	Sampling Event 2	Difference	Relative Percent Difference
Groundwater Sampling Locations	mg/L	mg/L	mg/L	%	mg/L	mg/L	mg/L	%	mg/L	mg/L	mg/L	%
MW-7	0.0032	0.0032	0	0%	0.14	0.15	0.01	7%	0.17	0.14	0.03	19%
MW-5	0.0019	0.003	0.0011	45%	0.1	0.11	0.01	10%	0.012	0.012	0	0%
MW-9	-	-	-	-	-	-	-	-	0.0073	0.0064	0.0009	13%
Headspace Sampling Locations	ug/m3	ug/m3	ug/m3	%	ug/m3	ug/m3	ug/m3	%	ug/m3	ug/m3	ug/m3	%
MW-3	12	40	28	108%	56	180	124	105%	-	-	-	-
MW-6	5	7	2	33%	57	43	14	28%	-	-	-	-
MW-9	-	-	-	-	15	7	8	73%	270	100	170	92%
Soil Gas Sampling Locations	ug/m3	ug/m3	ug/m3	%	ug/m3	ug/m3	ug/m3	%				
SG-5	16	7	9	78%	-	-	-	-				
SG-6	13	7	6	60%	-	-	-	-				
SG-7	10	< 5	5	67%	-	-	-	-				
SG-8	9	7	2	25%	-	-	-	-				
SG-9	23	22	1	4%	5	< 5	0	0%				
SG-10	27	24	3	12%	-	-	-	-				
SG-11	54	49	5	10%	14	13	1	7%				
SG-12	95	56	39	52%	6	8	2	29%				
Sub Slab Sampling Locations	ug/m3	ug/m3	ug/m3	%	ug/m3	ug/m3	ug/m3	%				
SS-1	130	140	10	7%	39	49	10	23%				
SS-2	16	18	2	12%	8	9	1	12%				
SS-3	22	18	4	20%	8	7	1	13%				
Indoor Air Sampling Location	ug/m3	ug/m3	ug/m3	%								
Indoor 1	< 5	7	2	33%								

NOTE:
1. - = Data not included in analysis because both analytical results were non-detect.

GROUNDWATER SERVICES, INC.

TABLE F.4
STATISTICAL ANALYSIS: LONGER-TERM TEMPORAL VARIABILITY AT ALTUS AFB

ESTCP: Vapor Intrusion Study

	TCE			PCE		
TEST SITE:	Altus Air Force Base			Altus Air Force Base		
TEST LOCATION:	Building 418			Building 418		
	Std. Deviation	Mean	Coeff. Of Var.	Std. Deviation	Mean	Coeff. Of Var.
Subslab Vapor Samples ug/m ^{3}						
Upgradient 1	49.90	62.67	0.80	427.20	530.00	0.81
Midgradient 2	13.13	12.27	1.07	67.84	61.67	1.10
Downgradient 3	15.89	15.17	1.05	281.73	216.67	1.30
Soil Gas Samples ug/m ^{3}						
Upgradient 4	NC	NC	NC	42.03	51.33	0.82
Midgradient 1	NC	NC	NC	39.40	55.00	0.72
Midgradient 2	NC	NC	NC	47.25	68.67	0.69
Midgradient 3	9.87	18.67	0.53	103.47	151.33	0.68
Midgradient 4	5.13	11.67	0.44	69.16	106.00	0.65
Downgradient 2	NC	NC	NC	50.01	41.67	1.20
Downgradient 3	NC	NC	NC	65.60	56.00	1.17
Downgradient 4	NC	NC	NC	63.34	58.67	1.08
Well Headspace Vapor Samples ug/m ^{3}						
Upgradient 1	17.96	17.30	1.04	112.28	107.00	1.05
Downgradient 1	NC	NC	NC	57.17	56.00	1.02
Downgradient 2	466.98	535.67	0.87	69.46	85.00	0.82
Groundwater Samples mg/L						
Upgradient 2	0.0004	0.0018	0.23	NC	NC	NC
Midgradient 4	0.0008	0.0010	0.82	NC	NC	NC
Downgradient 3	0.058	0.073	0.80	0.001	0.003	0.22
Downgradient 4	0.011	0.096	0.11	0.009	0.009	0.94

NOTES:
1. NC = Not Calculated

GROUNDWATER SERVICES, INC.

TABLE F.5
STATISTICAL ANALYSIS: LONGER-TERM TEMPORAL VARIABILITY AT HILL AFB

ESTCP: Vapor Intrusion Study

TEST SITE:	Residence #1		Residence #2	
TEST LOCATION:	Difference	RPD	Difference	RPD
Ambient Vapor Samples ug/m ^{3}				
Upgradient 1	0.141	1.18	NC	NC
Midgradient 2	0.003	0.07	NC	NC
Downgradient 3	0.052	0.75	NC	NC
Indoor Air Vapor Samples ug/m ^{3}				
Upgradient 1	0.028	0.39	0.034	0.37
Midgradient 2	0	0.00	0.072	0.86
Downgradient 3	0.015	0.20	0.14	1.17
Subslab Vapor Samples ug/m ^{3}				
Upgradient 1	18.8	1.77	NC	NC
Midgradient 2	12.1	1.01	NC	NC
Downgradient 3	28.9	1.41	NC	NC
Soil Gas Samples ug/m ^{3}				
Upgradient 4	12	0.57	NC	NC
Midgradient 1	28	1.17	NC	NC
Midgradient 2	114	1.01	NC	NC
Midgradient 3	120	0.60	NC	NC
Midgradient 4	170	0.87	NC	NC
Well Headspace Vapor Samples ug/m ^{3}				
Upgradient 1	3	0.21	3	0.19
Midgradient 1	19	0.24	11	0.34
Downgradient 1	13	0.38	320	0.84
Groundwater Samples mg/L				
Upgradient 2	NC	NC	0.00066	0.22
Upgradient 3	0.00157	0.45	0.00041	0.08
Upgradient 4	0.00256	0.64	0.00064	0.10
Midgradient 2	NC	NC	0.00111	1.69
Midgradient 3	0.00146	0.33	0.00039	0.17
Midgradient 4	0.0004	0.08	0.00247	0.52
Downgradient 1	NC	NC	0.00218	0.75
Downgradient 2	NC	NC	0.00094	0.26
Downgradient 3	0.00184	0.34	0.00203	0.33
Downgradient 4	0.00105	0.19	9.5E-05	0.01

NOTES:
1. All statistics based on TCE results
2. NC = Not Calculated

TABLE F.6
DUPLICATE VARIABILITY ANALYSIS: SAMPLE DUPLICATES

ESTCP: Vapor Intrusion Study

TCE Sample Type/ID	Background TCE Result	Duplicate TCE Result	Relative Percent Difference
Groundwater (mg/L)			
MW-7	0.14	0.14	0
MW-7	0.14	0.15	6.9
MW-5	0.0813	0.0875	7.3
MW-5	0.105	0.108	2.8
MW-10	<0.00038	<0.00038	NA
MW-4	0.0051	0.00535	4.8
MW-12	0.0053	0.00682	25
MW-4	0.00572	0.00596	4.1
MW-12	0.00673	0.00738	9.2
Soil gas (ug/m^3)			
SG-4	<5	<5	NA
SG-4	<5	<5	NA
SG-8	<5	6	18
SG-3	4.9	29	142
SG-8	<0.18	<0.18	NA
SG-4	30	24	22
SG-6	42	70	50
SG-8	<5	<5	NA
SG-12	12	13	8
SG-100	22	100	128
SG-3	<1200	<1900	NA
Sub slab (ug/m^3)			
SS-2	8	12	40
SS-3	7	6	15
SS-2	2.5	2.5	0
SS-3	<10	<10	NA
SS-2	19	17	11
SS-2	<0.92	<0.94	NA
Well headspace (ug/m^3)			
MW-2	30	18	50
MW-5	26	27	3.8
MW-6	38	31	20
Indoor (ug/m^3)			
Indoor 2	7.3	8.4	14
Indoor 2	0.18	0.18	0
Indoor 2	0.056	<0.056	NA
Indoor 2	<0.048	0.071	39
Indoor 2	0.13	0.13	0
Ambient (ug/m^3)			
Ambient 3	<0.05	<0.039	NA
Ambient 2	<0.054	0.084	43

NOTES:
1. Detection limit indicated used for non-detect values.
2. RPD not calculated when both sample results non-detect (NA).
3. < = Sample not detected at indicated detection limit.

TABLE F.6
DUPLICATE VARIABILITY ANALYSIS: SAMPLE DUPLICATES

ESTCP: Vapor Intrusion Study

PCE

Sample Type/ID	Background PCE Result	Duplicate PCE Result	Relative Percent Difference
Groundwater (mg/L)			
MW-7	0.003	0.0033	9.5
MW-7	0.0033	0.0031	6.3
MW-5	0.00323	0.00302	6.7
MW-5	0.00638	0.00525	19
MW-10	<0.00042	<0.00042	NA
Soil gas (ug/m^3)			
SG-4	<5	<5	NA
SG-4	7	6	15
SG-8	7	6	15
SG-3	98	260	91
SG-8	40	34	16
SG-4	<10	<10	NA
SG-6	<10	<10	NA
SG-8	7.8	170	182
SG-12	<10	<10	NA
SG-100	<10	<10	NA
SG-3	<1200	<1900	NA
Sub slab (ug/m^3)			
SS-2	130	140	7.4
SS-3	18	16	12
SS-2	86	85	1.2
SS-3	<10	<10	NA
SS-2	<0.92	<0.9	NA
SS-2	<0.92	<0.94	NA
Well headspace (ug/m^3)			
MW-2	<10	<10	NA
MW-5	13	11	17
MW-6	<10	<10	NA
Indoor (ug/m^3)			
Indoor 2	0.21	0.19	10
Indoor 2	0.63	0.59	6.6
Indoor 2	0.086	0.09	4.5
Indoor 2	0.17	0.16	6.1
Indoor 2	0.073	0.2	93
Ambient (ug/m^3)			
Ambient 3	0.081	0.095	16
Ambient 2	0.058	0.24	122

NOTES:
1. Detection limit indicated used for non-detect values.
2. RPD not calculated when both sample results non-detect (NA).
3. < = Sample not detected at indicated detection limit.

TABLE F.6
DUPLICATE VARIABILITY ANALYSIS: SAMPLE DUPLICATES

ESTCP: Vapor Intrusion Study

cis 1,2-DCE

Sample Type/ID	Background cis 1,2-DCE Result	Duplicate cis 1,2-DCE Result	Relative Percent Difference
Groundwater (mg/L)			
MW-7	0.015	0.018	18
MW-7	0.014	0.014	0
MW-5	0.0064	0.00643	0.47
MW-5	0.0186	0.02	7.3
MW-10	<0.002	<0.002	NA
MW-4	<0.00024	<0.00024	NA
MW-12	<0.00024	<0.00024	NA
MW-4	<0.00027	<0.00024	NA
MW-12	<0.00024	<0.00024	NA
Well headspace (ug/m3)			
MW-2	NA	NA	NA
MW-5	<5	<5	NA
MW-6	NA	NA	NA

Radon

Sample Type/ID	Background Radon Result	Duplicate Radon Result	Relative Percent Difference
Sub slab (pCi/L)			
SS-3	479	480	0.21
SS-3	0.4	<0.4	0
SS-1	601	641	6.4
SS-2	559	543	2.9
SS-3	542	542	0
SS-1	931	1002	7.3
SS-3	194	192	1.0
SS-2	691	670	3.1
Indoor (pCi/L			
Indoor 1	<0.4	<0.4	NA
Indoor 3	<0.4	<0.4	NA
Indoor 4	0.4	0.5	22
Indoor 1	0.4	<0.4	0
Indoor 2	<0.4	<0.4	NA
Indoor 2	0.46	0.36	24
Ambient (pCi/L)			
Ambient	0.14	0.12	15
Ambient	0.3	0.3	0

SF_6

Sample Type/ID	Background SF_6 Result	Duplicate SF_6 Result	Relative Percent Difference
Air exchange Sub slab (ppbv)			
SS-2	0.92	1	8.3
SS-2	0.22	0.076	97
SS-2	55	43	24
SS-2	8.3	7	17
Air Exchange Indoor			
Indoor 2	2.4	2.3	4.3
Indoor 2	5.7	5.4	5.4
Indoor 1	33	31	6.3
Indoor 2	14	15	6.9
Indoor 2	11	11	0
Leak Tracer Soil gas(ppbv)			
SG-3	250	0.23	200
SG-8	0.15	0.18	18

NOTES:
1. Detection limit indicated used for non-detect values.
2. RPD not calculated when both sample results non-detect (NA).
3. < = Sample not detected at indicated detection limit.

GSI ENVIRONMENTAL

TABLE F.7
DUPLICATE VARIABILITY ANALYSIS: LABORATORY DUPLICATES

ESTCP: Vapor Intrusion Study

Sample ID	Compound	Background Result	Duplicate Result	Relative Percent Difference
TO-15 (ug/m^3)				
U5-928.101 (SG-1)	Trichloroethene (TCE)	0.058	0.058	**0**
	Tetrachloroethene (PCE)	0.077	0.078	**1.3**
U5-1924A (SG-1)	Trichloroethene (TCE)	1500	1500	**0**
	Tetrachloroethene	1500	1500	**0**
U5-928.100 (Ind-2)	Trichloroethene (TCE)	0.13	0.12	**8**
	Tetrachloroethene (PCE)	0.073	0.073	**0**
SG-3	Trichloroethene (TCE)	4.9	5	**2**
	Tetrachloroethene (PCE)	98	100	**2**
QC-C (SG-3)	Trichloroethene (TCE)	29	30	**3.4**
	Tetrachloroethene (PCE)	260	270	**3.8**
QC-G (Ind-2)	Trichloroethene (TCE)	8.4	8.4	**0**
	Tetrachloroethene (PCE)	0.19	0.2	**5.1**
Ambient 3	Trichloroethene (TCE)	0.087	0.093	**6.7**
	Tetrachloroethene (PCE)	0.21	0.2	**4.9**
SS-1	Trichloroethene (TCE)	29	28	**3.5**
	Tetrachloroethene (PCE)	480	470	**2.1**
SG-8	Trichloroethene (TCE)	1.1	1.1	**0**
	Tetrachloroethene (PCE)	33	32	**3.1**
SF6 (ppbv)				
QC D (SS-2)	Sulfur Hexafluoride (SF_6)	43	44	**2.3**
US-928.100 (Ind-2)	Sulfur Hexafluoride (SF6)	100	100	**0**
U5-928.103 (Ind-4)	Sulfur Hexafluoride (SF6)	69	69	**0**
U5-928.103 (Ind-4)	Sulfur Hexafluoride (SF6)	100	100	**0**
Ambient 1	Sulfur Hexafluoride (SF6)	88	87	**1.1**
SG-7	Sulfur Hexafluoride (SF6)	70	68	**2.9**
SG-4	Sulfur Hexafluoride (SF6)	4800000	4900000	**2.1**
SS-1	Sulfur Hexafluoride (SF6)	210	210	**0**

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix G

Project Database of Analytical Results

Data File	Database of Analytical Results
Table G.1	Database Structure
Table G.2	Geotechnical Data Summary
Figure G.1	Location of Altus AFB Demonstration Building
Figure G.2	Location of Hill AFB Demonstration Buildings
Figure G.3	Sampling Locations: Altus AFB Building #418
Figure G.4	Sampling Locations: Hill AFB Residence #1
Figure G.5	Sampling Locations: Hill AFB Residence #2
Figure G.6	Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology: Altus AFB Building #418
Figure G.7	Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology: Hill AFB Residence #1
Figure G.8	Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology: Hill AFB Residence #2

GROUNDWATER SERVICES, INC.

TABLE G.1
DATABASE STRUCTURE

ESTCP: Vapor Intrusion Study

ANALYTICAL RESULTS

Table 1A: Analytical Location Data
Site
LocationID
GSISampleID
GroundElevation
WellTotalDepth
ScreenTop
ScreenBottom
ScreenInterval
Matrix

Table 1B: Analytical Data
Site
LocationID
GSISampleID
DepthTop
DepthBottom
DepthInterval
SampleType
Matrix
SampleDate
SampleTime
Constituent
Result
Flag
DetectionLimit
ReportingLimit
Units
DilutionFactor
SampleCollectionMethod
CasingOrLineVolume_cc
LineVolumePurged_cc
CASNo
AnalyticalMethod
Lab

Table 1C: Rejected TO-15 Analytical Data
Site
LocationID
GSISampleID
DepthTop
DepthBottom
DepthInterval
SampleType
Matrix
SampleDate
SampleTime
Constituent
Result
Flag
DetectionLimit
ReportingLimit
Units
DilutionFactor
SampleCollectionMethod
CasingOrLineVolume_cc
LineVolumePurged_cc
CASNo
AnalyticalMethod
Lab

GEOTECHNICAL INFORMATION

Table 2A: Geotechnical Location Data
Site
LocationID
GSISampleID
Matrix
DepthTop
DepthBottom
DepthInterval

Table 2B: Geotechnical Data
Site
LocationID
GSISampleID
DepthTop
DepthBottom
DepthInterval
SampleType
Matrix
SampleDate
Constituent
Result
Flag
DetectionLimit
Units
CASNo
AnalyticalMethod
Lab

STATIC WATER LEVEL INFORMATION

Table 3: Water Level Data
Site
LocationID
SampleDate
DepthToWater
NoDepthReason

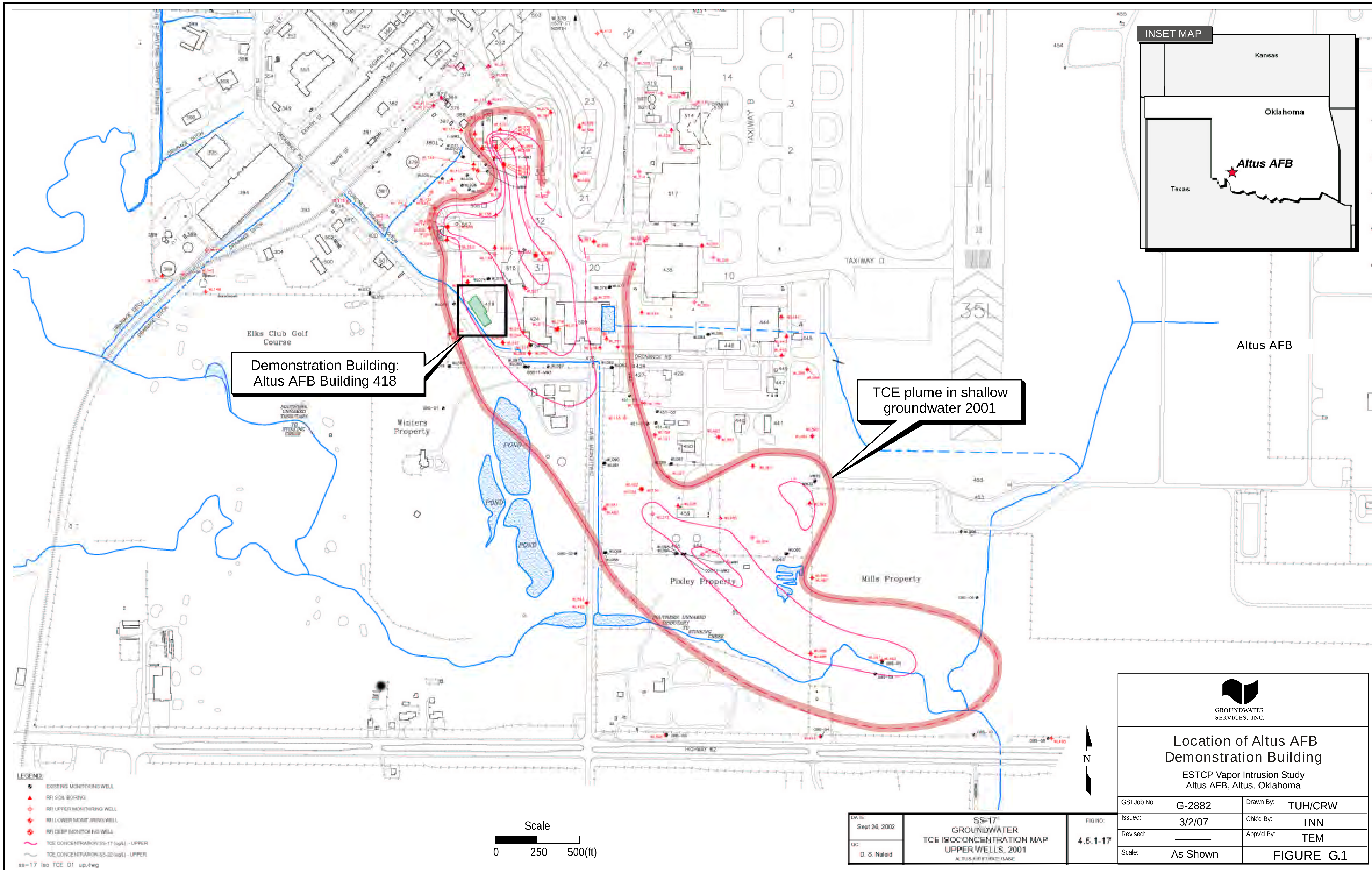
Note: Colors indicate database fields that link individual tables.

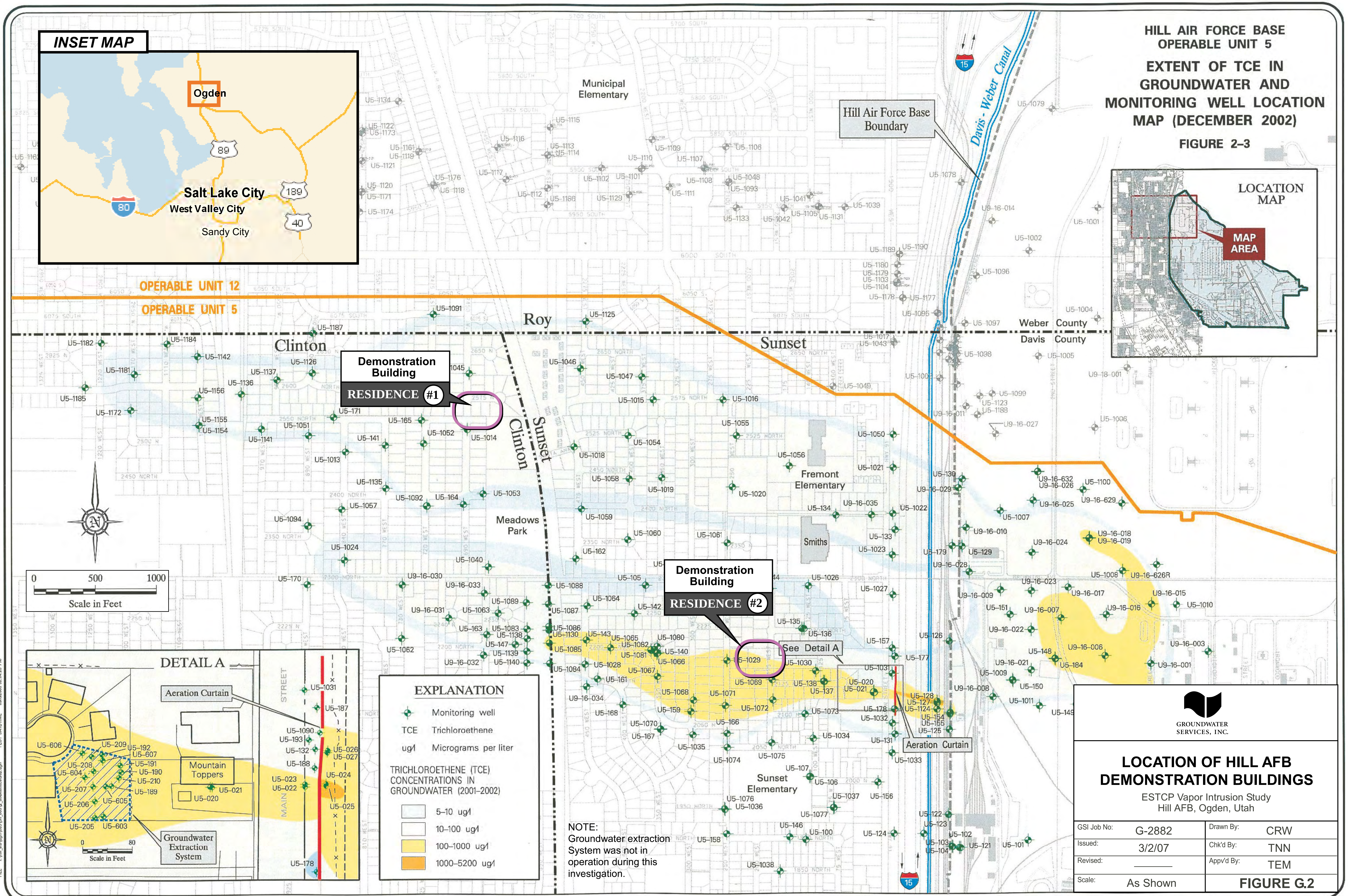
GROUNDWATER SERVICES, INC.

TABLE G.2
GEOTECHNICAL DATA SUMMARY
ESTCP: Vapor Intrusion Study

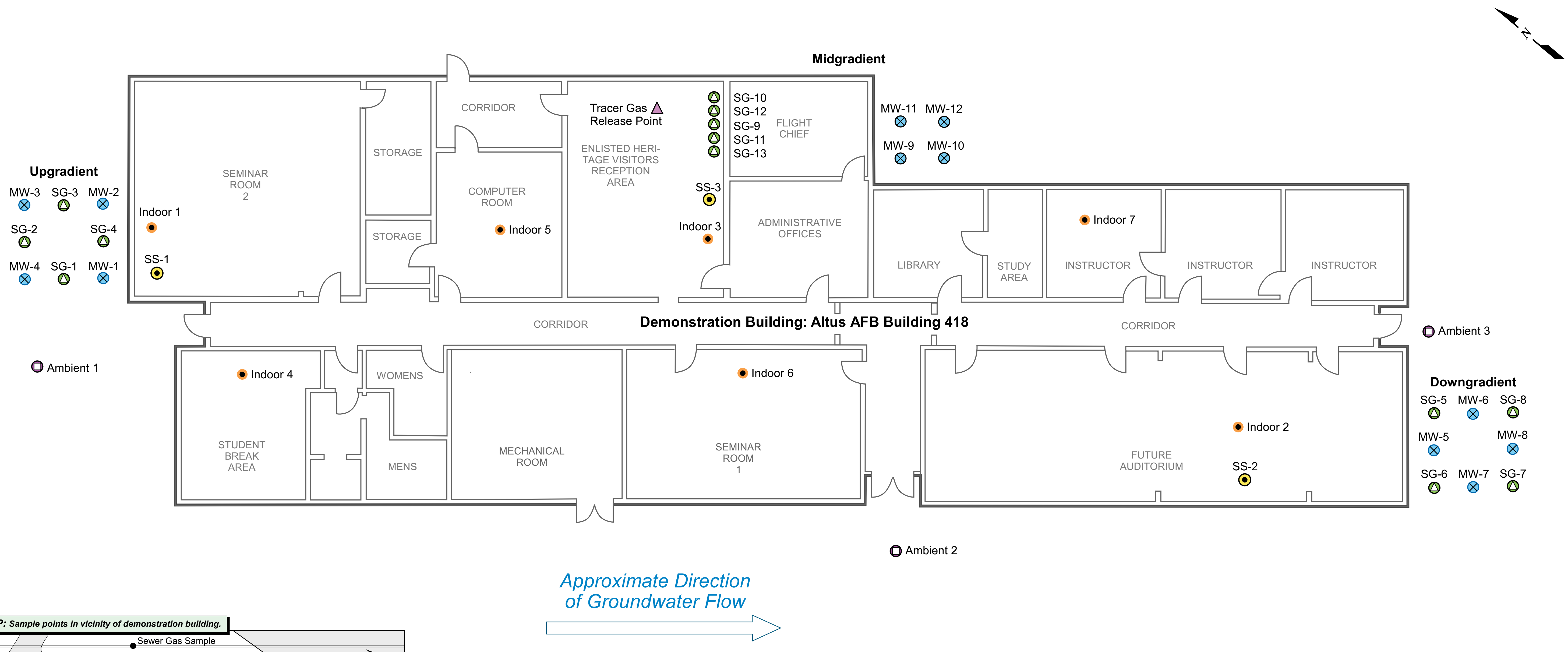
LOCATION ID.	SAMPLE DEPTH	BULK DENSITY	FRACTION ORGANIC CARBON	POROSITY TOTAL	POROSITY AIR FILLED	POROSITY WATER FILLED	INTRINSIC PERMEABILITY TO WATER (25 PSI CONFINING STRESS)	NATIVE HYDRAULIC CONDUCTIVITY (25 PSI CONFINING STRESS)
Units	ft.	kg/L	g/g	%Vb	%Vb	% Vb	cm^2	cm/s
Altus Air Force Base, Altus, Oklahoma								
MW-2	1-2	1.49	5.55E-03	43.1	13.5	69	4.18E-12	4.05E-07
MW-2	4-5	1.72	1.20E-03	35.1	9.2	74	4.24E-13	4.15E-08
MW-2	7-8	1.6	1.60E-03	40.4	13.9	65	1.87E-12	1.86E-07
MW-6	2-3	1.62	9.20E-03	38.1	11.2	71	2.48E-12	2.45E-07
MW-6	5.5-6.5	1.63	1.50E-03	39.6	14.5	63	1.18E-11	1.18E-06
MW-6	7.5-8.5	1.65	7.90E-04	38.6	10	74	3.35E-12	3.28E-07
MW-10	2-3	1.6	5.05E-03	39.1	13.5	65	2.85E-12	2.76E-07
MW-10	5-6	1.67	1.15E-03	36.7	8.6	77	7.14E-13	6.97E-08
MW-10	7-8	1.63	9.90E-03	39.1	9.7	75	2.30E-12	2.25E-07
Hill Air Force Base, Ogden, Utah Residence #1								
MW-3	3-4	1.61	3.65E-03	39.6	3.8	35.8	4.58E-11	4.60E-06
MW-3	7-8	1.58	6.70E-03	41.1	4.8	36.3	4.67E-11	4.69E-06
MW-3	11-12	1.51	3.35E-03	43.8	6.7	37.1	3.07E-11	3.09E-06
MW-8	5-6	1.66	5.75E-03	37.0	1.2	35.8	7.66E-11	7.67E-06
MW-8	8-9	1.37	1.60E-03	48.5	10.0	38.5	1.23E-10	1.23E-05
MW-8	10-11	1.51	2.90E-04	43.9	4.2	39.7	4.06E-11	4.08E-06
MW-11	2-3	1.38	3.05E-03	47.7	9.3	38.4	1.13E-10	1.14E-05
MW-11	7-8	1.50	3.45E-03	44.0	5.6	38.5	7.56E-12	7.65E-07
MW-11	9-10	1.46	<1.00E-04	45.7	1.8	44.0	1.90E-11	1.91E-06
Hill Air Force Base, Ogden, Utah Residence #2								
MW-4	2-3	1.62	4.95E-03	38.6	11.9	26.7	1.78E-10	1.77E-05
MW-4	8-9	1.57	4.35E-03	40.8	11.1	29.7	8.96E-11	8.82E-06
MW-4	12-13	1.61	6.10E-03	39.4	8.1	31.3	5.38E-09	5.33E-04
MW-8	3-4	1.65	6.55E-03	37.4	17.2	20.1	8.89E-10	8.82E-05
MW-8	7-8	1.50	2.50E-04	43.5	11.0	32.5	5.44E-11	5.41E-06
MW-8	11-12	1.48	2.35E-03	44.4	11.6	32.8	1.20E-10	1.19E-05
MW-12	4-5	1.49	5.50E-03	44.1	13.8	30.3	1.01E-10	1.00E-05
MW-12	9-10	1.58	3.30E-03	40.7	11.9	28.7	1.78E-09	1.77E-04
MW-12	14-15	1.51	1.85E-03	43.2	12.9	30.3	5.92E-09	5.87E-04

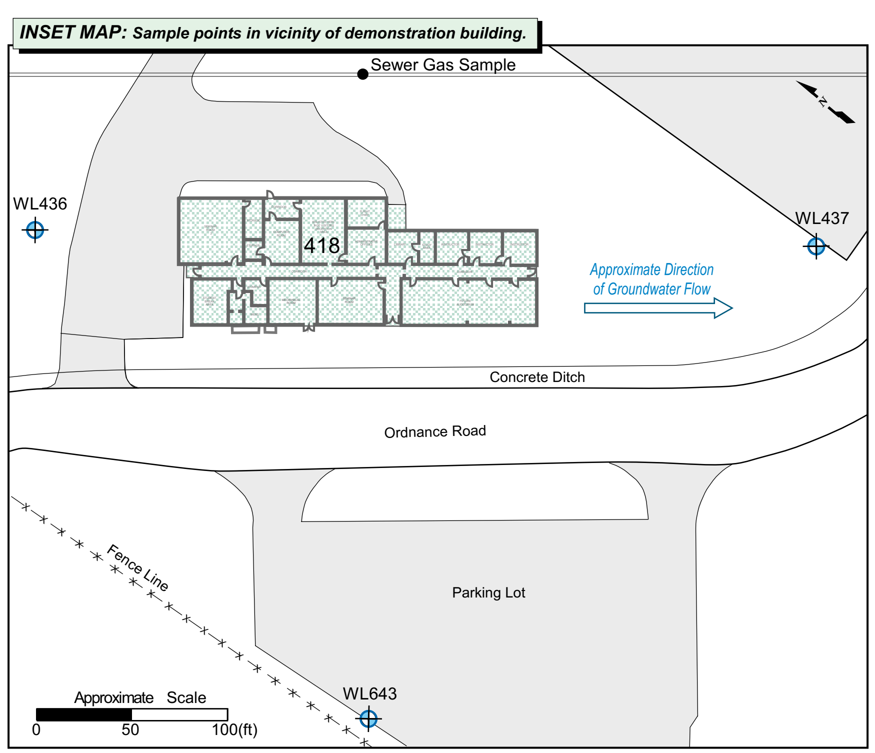
Notes:
1) Analysis performed by PTS Laboratories, Houston, Texas.
2) Fraction Organic Carbon determined by Walkley-Black method, intrinsic permeability and hydraulic conductivity determined by EPA 9100, vol. moisture content determined by ASTM D2216 & API RP40, all other analyses by API RP40.
3) All sample orientations were vertical.
4) Vb = bulk volume.


INSET MAP
Kansas
Oklahoma
Altus AFB
Texas
Altus AFB
Demonstration Building:
Altus AFB Building 418
TCE plume in shallow
groundwater 2001
Elks Club Golf
Course
Winters
Property
Pixley Property
Mills Property
POND
TAXIWAY B
TAXIWAY D
HIGHWAY 62
LEGEND
EXISTING MONITORING WELL
RFI SOIL BORING
RFI UPPER MONITORING WELL
RFI LOWER MONITORING WELL
RFI DEEP MONITORING WELL
TCE CONCENTRATION SS-17 (ug/L) - UPPER
TCE CONCENTRATION SS-20 (ug/L) - UPPER
Scale
0
250
500(ft)
N
SS-17
GROUNDWATER
TCE ISOCONCENTRATION MAP
UPPER WELLS, 2001
ALTUS AIR FORCE BASE
Sept 24, 2002
4.5.1-17
GROUNDWATER SERVICES, INC.
Location of Altus AFB
Demonstration Building
ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma
GSI Job No: G-2882
Drawn By: TUH/CRW
Issued: 3/2/07
Chk'd By: TNN
Revised:
Appv'd By: TEM
Scale: As Shown
FIGURE G.1



HILL AIR FORCE BASE
OPERABLE UNIT 5
EXTENT OF TCE IN GROUNDWATER AND MONITORING WELL LOCATION MAP (DECEMBER 2002)
FIGURE 2–3
INSET MAP
Ogden
Salt Lake City
West Valley City
Sandy City
LOCATION MAP
MAP AREA
OPERABLE UNIT 12
OPERABLE UNIT 5
Hill Air Force Base Boundary
Davis - Weber Canal
Municipal Elementary
Clinton
Roy
Sunset
Clinton
Sunset
Weber County
Davis County
Demonstration Building
RESIDENCE #1
Demonstration Building
RESIDENCE #2
Fremont Elementary
Meadows Park
Smiths
Sunset Elementary
See Detail A
Aeration Curtain
Scale in Feet
0
500
1000
DETAIL A
Aeration Curtain
Mountain Toppers
Groundwater Extraction System
STREET
MAIN
EXPLANATION
Monitoring well
TCE Trichloroethene
ug/l Micrograms per liter
TRICHLOROETHENE (TCE) CONCENTRATIONS IN GROUNDWATER (2001–2002)
5–10 ug/l
10–100 ug/l
100–1000 ug/l
1000–5200 ug/l
NOTE:
Groundwater extraction System was not in operation during this investigation.
GROUNDWATER SERVICES, INC.
LOCATION OF HILL AFB DEMONSTRATION BUILDINGS
ESTCP Vapor Intrusion Study
Hill AFB, Ogden, Utah
GSI Job No: G-2882
Issued: 3/2/07
Revised:
Scale: As Shown
Drawn By: CRW
Chk'd By: TNN
Appv'd By: TEM
FIGURE G.2





LEGEND

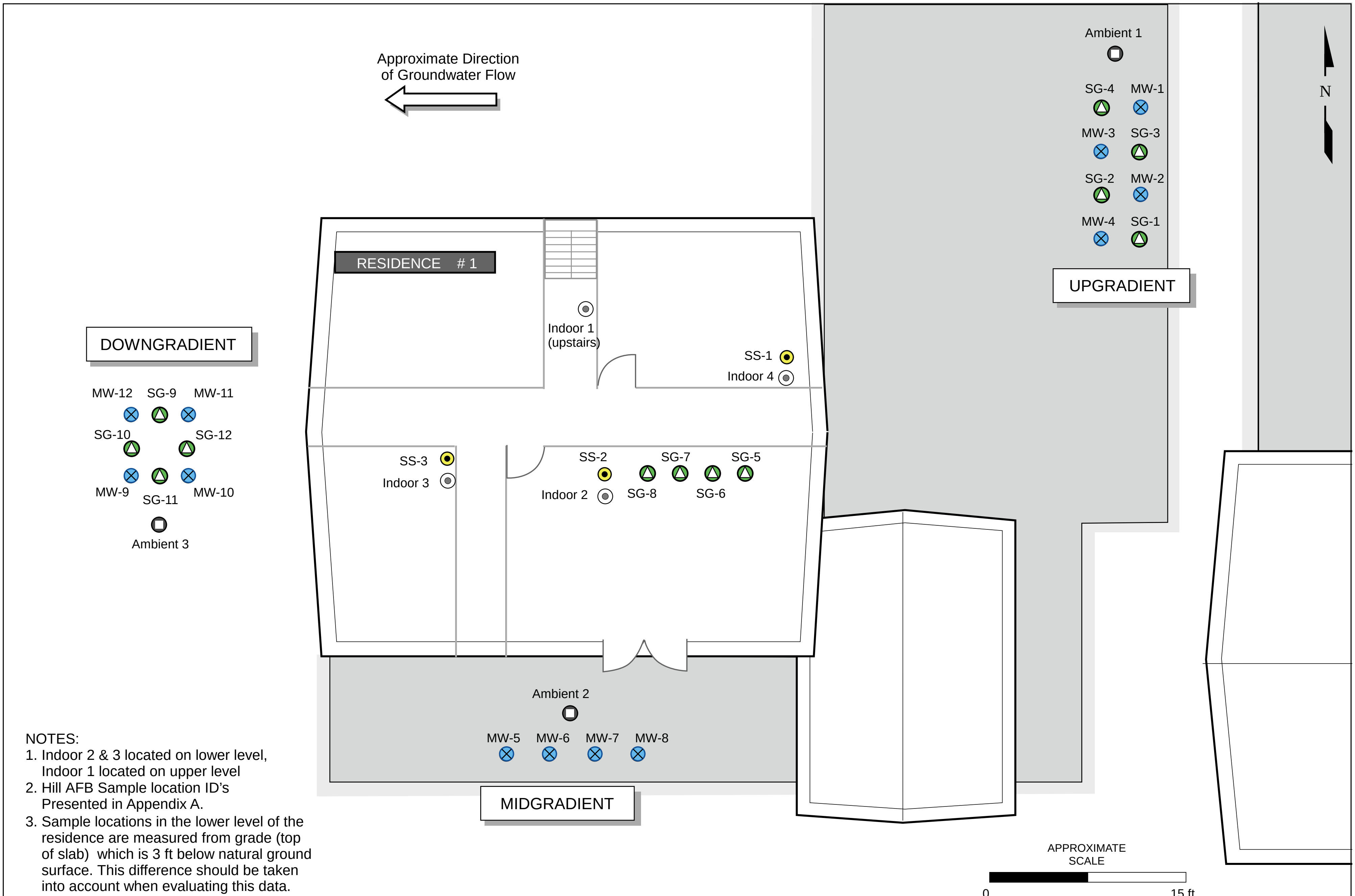
- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling port
- Existing 2" monitoring well screened in the upper water-bearing unit.

GROUNDWATER SERVICES, INC.

Sampling Locations

ESTCP Vapor Intrusion Study
Altus AFB, Altus, Oklahoma

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	———	Appv'd By:	TEM
Scale:	As Shown		FIGURE G.3



NOTES:

1. Indoor 2 & 3 located on lower level, Indoor 1 located on upper level
2. Hill AFB Sample location ID's Presented in Appendix A.
3. Sample locations in the lower level of the residence are measured from grade (top of slab) which is 3 ft below natural ground surface. This difference should be taken into account when evaluating this data.

LEGEND

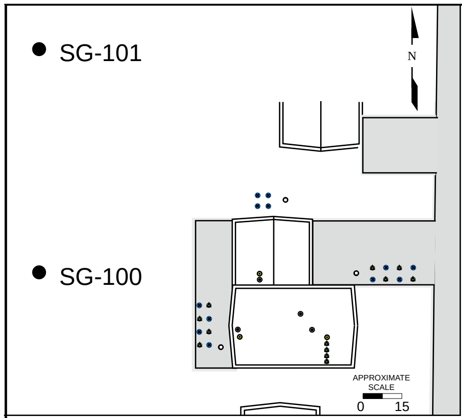
- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling point
- Concrete

GROUNDWATER SERVICES, INC.

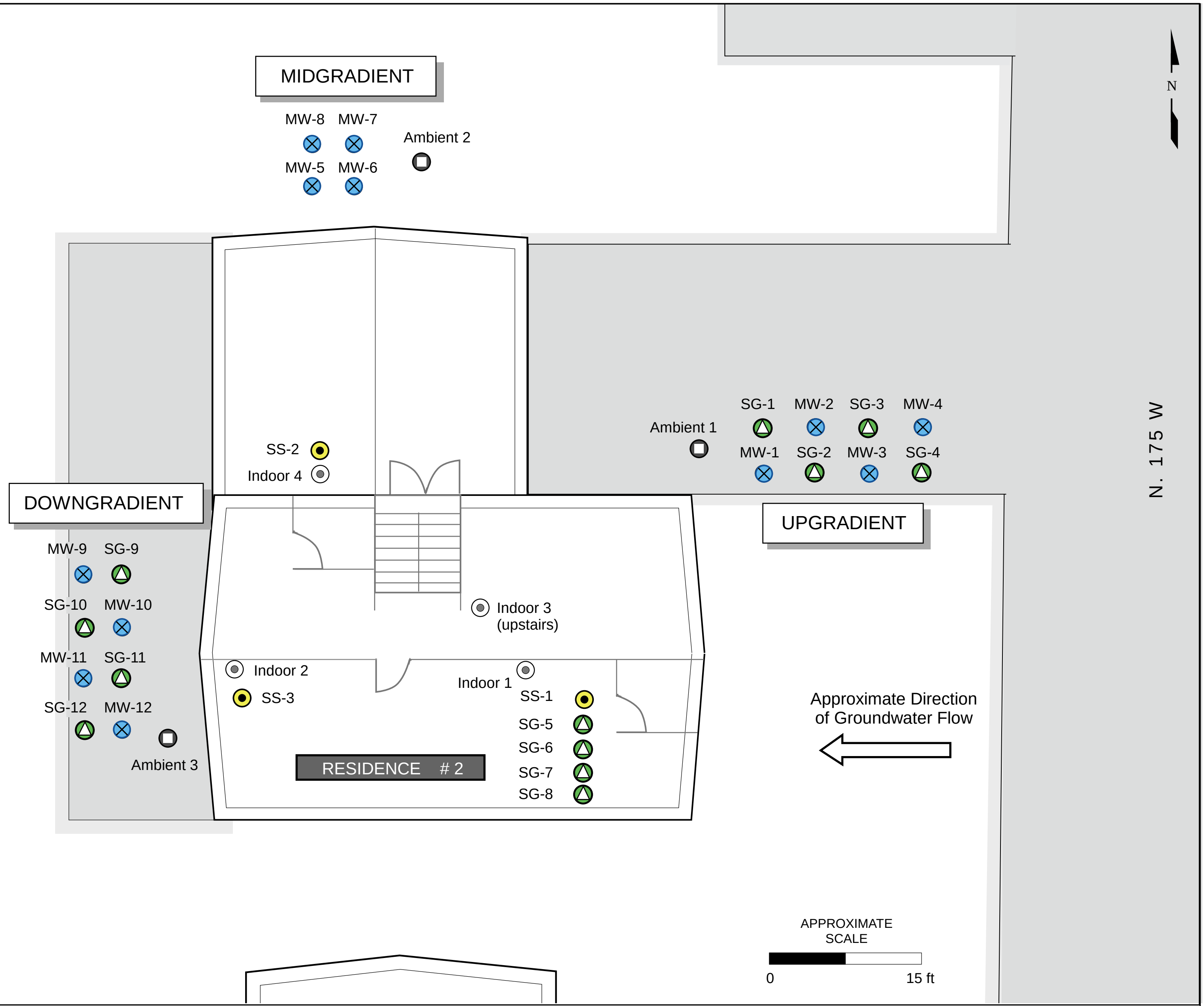
GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	________	Appv'd By:	TNN
Scale:	As shown	FIGURE G.4	

SAMPLING LOCATIONS:
Hill AFB RESIDENCE #1

ESTCP Vapor Intrusion Study
Hill AFB, Ogden, Utah



Approximate Location
of SG-100 and SG-101



NOTES:

1. Indoor 1 & 2 located on lower level, Indoor 3 located on upper level
2. Hill AFB Sample location ID's Presented in Appendix A.
3. Sample locations in the lower level of the residence are measured from grade (top of slab) which is 3 ft below natural ground surface. This difference should be taken into account when evaluating this data.

LEGEND

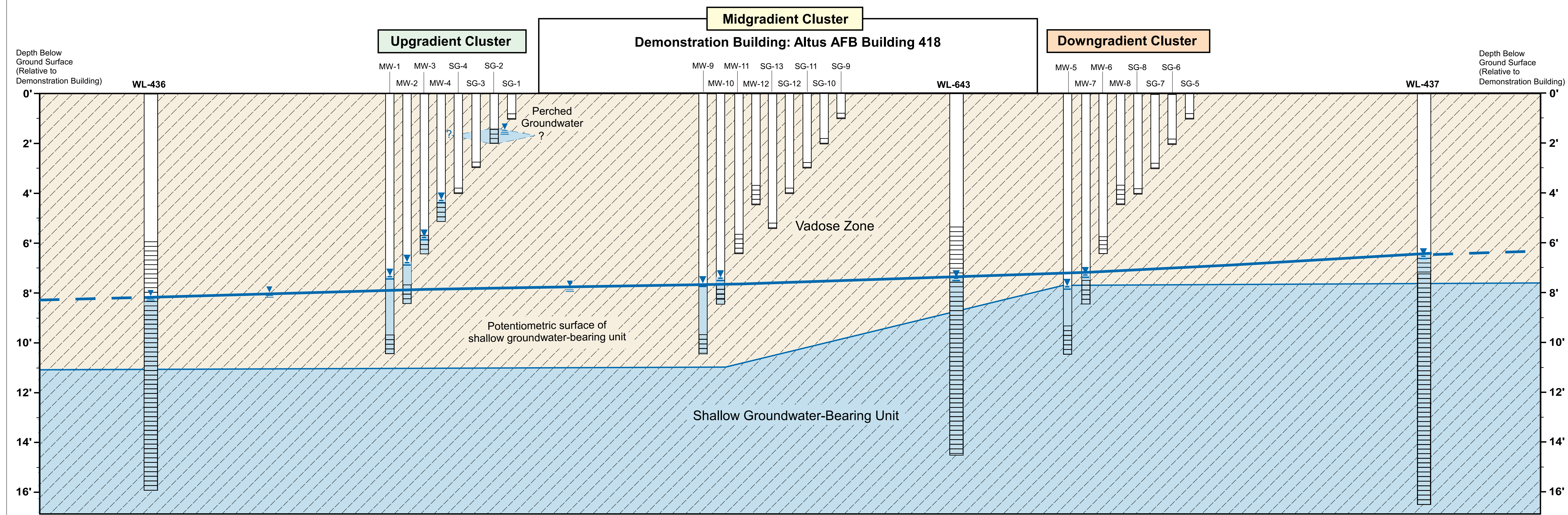
- Ambient sample location
- Indoor air sample location
- Monitoring well location
- Soil gas sample point
- Sub-slab sampling point
- Concrete

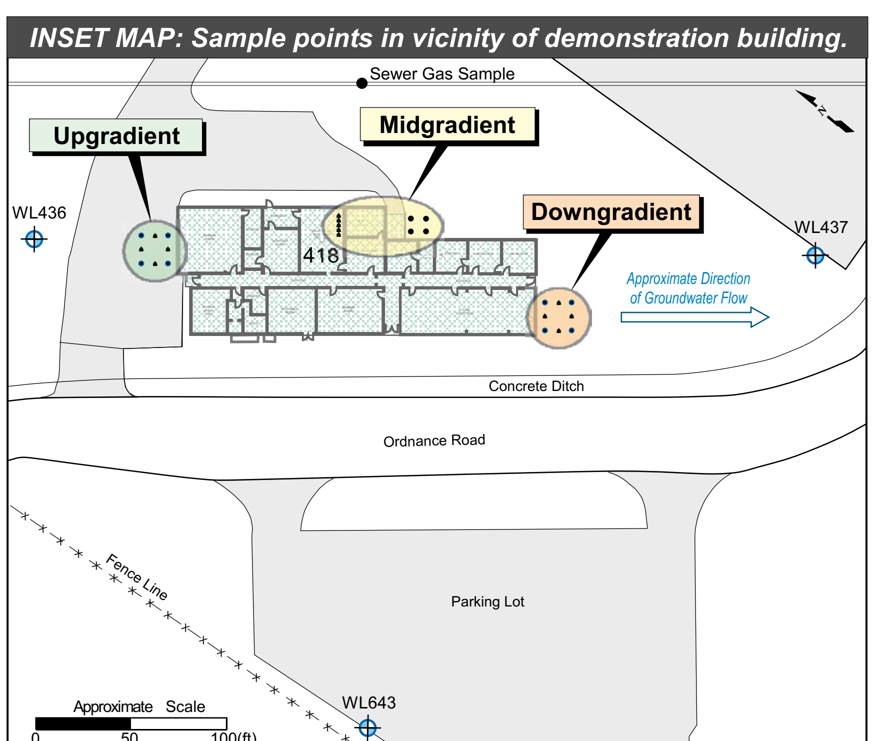
GROUNDWATER SERVICES, INC.

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/06	Chk'd By:	TNN
Revised:	________	Appv'd By:	TNN
Scale:	As shown	FIGURE G.5	

SAMPLING LOCATIONS:
Hill AFB RESIDENCE #2

ESTCP Vapor Intrusion Study
Hill AFB, Ogden, Utah





LEGEND

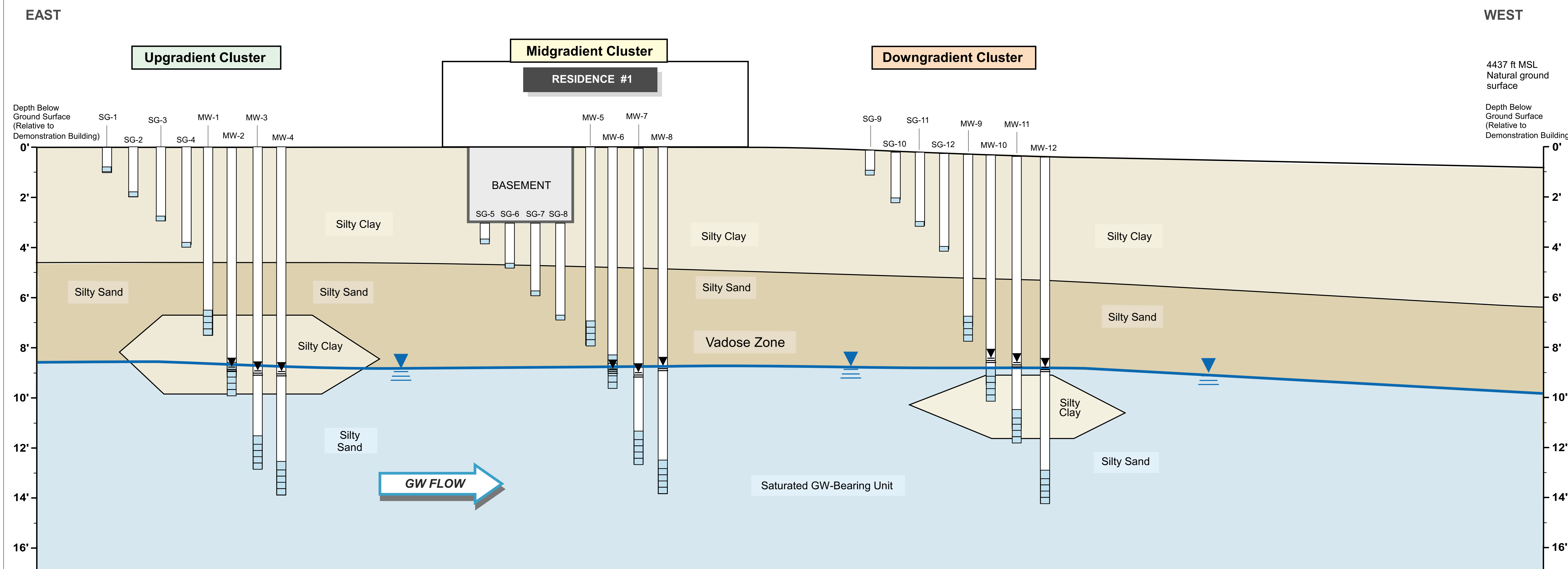
- Static water level measured on 12/19/06
- Screen Interval
- Silty Clay Soil Type

GROUNDWATER SERVICES, INC.

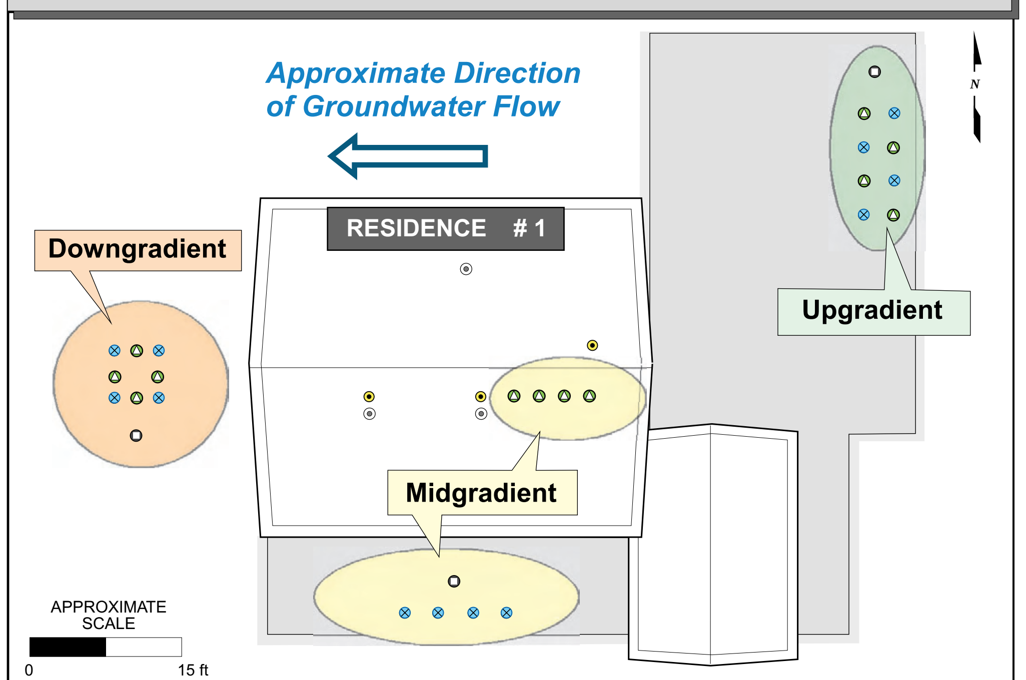
Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology: Altus AFB Building #418

ESTCP Vapor Intrusion Study

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	———	Appv'd By:	TEM
Scale:	Not to Scale		**FIGURE G.6**



INSET MAP: Sample points in vicinity of demonstration building.



SCALE
Horizontal: Not to Scale
Vertical: 1 in = 4 ft

LEGEND

- Static water level measured on 3/13/06
- Screen Interval
- Silty Clay Soil Type
- Silty Sand Soil Type

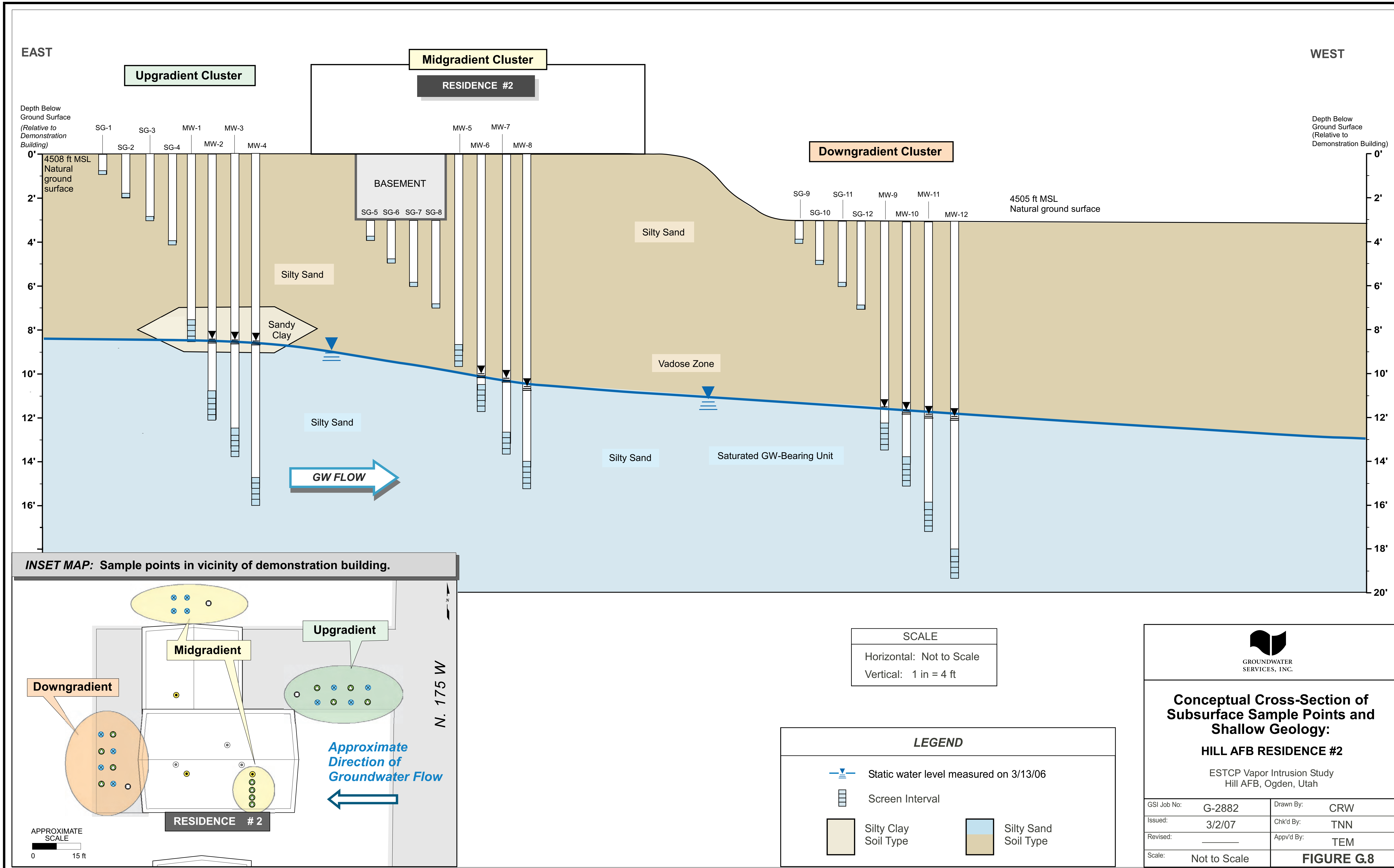
GROUNDWATER SERVICES, INC.

Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology:

HILL AFB RESIDENCE #1

ESTCP Vapor Intrusion Study
Hill AFB, Ogden, Utah

GSI Job No:	G-2882	Drawn By:	CRW
Issued:	3/2/07	Chk'd By:	TNN
Revised:	———	Appv'd By:	TEM
Scale:	Not to Scale		FIGURE G.7



EAST
WEST
Upgradient Cluster
Midgradient Cluster
RESIDENCE #2
Downgradient Cluster
Depth Below Ground Surface (Relative to Demonstration Building)
SG-1
SG-2
SG-3
SG-4
MW-1
MW-2
MW-3
MW-4
MW-5
MW-6
MW-7
MW-8
SG-5 SG-6 SG-7 SG-8
BASEMENT
SG-9
SG-10
SG-11
SG-12
MW-9
MW-10
MW-11
MW-12
4508 ft MSL Natural ground surface
4505 ft MSL Natural ground surface
0'
2'
4'
6'
8'
10'
12'
14'
16'
18'
20'
Silty Sand
Sandy Clay
Vadose Zone
Saturated GW-Bearing Unit
GW FLOW
INSET MAP: Sample points in vicinity of demonstration building.
Upgradient
Midgradient
Downgradient
RESIDENCE # 2
N. 175 W
Approximate Direction of Groundwater Flow
APPROXIMATE SCALE
0
15 ft
SCALE
Horizontal: Not to Scale
Vertical: 1 in = 4 ft
LEGEND
Static water level measured on 3/13/06
Screen Interval
Silty Clay Soil Type
Silty Sand Soil Type
GROUNDWATER SERVICES, INC.
Conceptual Cross-Section of Subsurface Sample Points and Shallow Geology:
HILL AFB RESIDENCE #2
ESTCP Vapor Intrusion Study
Hill AFB, Ogden, Utah
GSI Job No: G-2882
Issued: 3/2/07
Revised:
Scale: Not to Scale
Drawn By: CRW
Chk'd By: TNN
Appv'd By: TEM
FIGURE G.8

July 31, 2007

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix H

Health and Safety Plan

GROUNDWATER SERVICES, INC.

HEALTH AND SAFETY PLAN
GROUNDWATER SERVICES, INC.

2211 Norfolk, Suite 1000
Houston, Texas 77098
713-522-6300

Revised: June 2004

TABLE OF CONTENTS
GSI Health and Safety Plan

TABLE OF CONTENTS
GSI Health and Safety Plan

GROUNDWATER SERVICES, INC.

GROUNDWATER SERVICES, INC.
HEALTH AND SAFETY PLAN
(GSI HASP)

1.0 GSI HEALTH AND SAFETY POLICY

1.1 Purpose, Scope, and Applicability

Purpose. Groundwater Service, Inc. (GSI), is committed to providing a safe and healthy working environment for all of its employees, and to ensuring that our safety performance meets or exceeds our customers' expectations. Accordingly, GSI has developed this written Health and Safety Plan (the GSI HASP) in order to promote safety awareness and safe working practices; establish procedures for safe implementation of field activities; address safety-related concerns; and prevent accidents, injuries and occupational illness.

Scope. The GSI HASP provides safe practices for fieldwork on jobsites owned and operated by GSI clients and others. Each site may have specific rules, practices or other requirements not specified in this HASP which must be adhered too, as applicable. The GSI HASP has been designed to comply with applicable standards of the Occupational Safety and Health Administration (OSHA), promulgated in Chapter 29 of the Code of Federal Regulations (29 CFR), which relate to our core business activities in the field of environmental consulting and engineering (SIC 8744). Specifically addressed are requirements Hazardous Waste Operations and Emergency Response ("HAZWOPER," §1910.120); Subpart I, Personal Protective Equipment (PPE, §1910.132–1910.138) including Respiratory Protection (§1910.134); and the Hazard Communication Standard ("HAZCOM," § 1910.1200). Other standards are addressed as applicable. In addition to the main body of this plan, supplemental sections governing Substance Abuse, Driver Safety, Hazard Communication (Hazcom), and Energy Isolation (Lock-out/Tag-out) are included as appendices. Additional sections will be prepared and distributed as needed.

The GSI HASP is designed to accompany, and to be used in conjunction with, site-specific and project-specific HASPs. As allowed by OSHA, the company HASP may be used to specify standard operating procedures, which need not de duplicated in the site-specific plan. **THE GSI HASP AND SITE-SPECIFIC HASP MUST BE ONSITE AND AVAILABLE TO SITE WORKERS, INCLUDING GSI EMPLOYEES AND SUBCONTRACTORS AT ALL TIMES WHEN FIELDWORK IS BEING PERFORMED.**

Health and safety issues and procedures in the office and warehouse environment, including, but not limited to, fire safety and emergency building evacuation procedures are addressed in the GSI Employee Manual. However, applicable elements of this HASP apply in the office and other facilities and locations, as well as on fieldwork sites.

Applicability. The plan applies to all GSI employees working both at GSI facilities (office and warehouse/shop locations), and at all field sites located on the facilities and properties of GSI clients. The principles and safe work practices described in this

program also apply to our subcontractors. GSI employees supervising the work of subcontractors are responsible for communicating the requirements of this program to subcontract personnel and for ensuring their conformance with our safety requirements.

Conformance with all elements of the GSI HASP is mandatory. All GSI employees are expected to take primary responsibility for their own safety, to exercise sound judgment, and to make the safe performance of their jobs their first priority. All are required to conduct all work in a safe and careful manner in accordance with the GSI HASP and project- or site-specific safety plans. Failure to abide by the plan may result in disciplinary action, including dismissal, depending on the severity of the violation.

1.2 Program Distribution and Revision

The GSI Health and Safety Plan is distributed to all GSI employees and is readily available to all employees via the computer network server. A copy of the plan is provided to all new employees upon acceptance of employment at GSI. An orientation to the plan is conducted by the GSI Safety Administrator, and each new employee must read, understand, and agree to abide by all aspects of the GSI Health and Safety Program, and must certify in writing their understanding of the program and the requirement to abide by the plan.

The GSI HASP will be updated or augmented as necessary to account for expansion of the services provided, revisions in applicable regulations, and to address the needs of our clients. Plan updates will be distributed to all GSI employees. Upon each revision, the current GSI HASP will be available on the network server (WINSERVER2/ Win_Jobs/ 0General Office) and may be downloaded and printed by all employees.

GSI welcomes input from employees with suggestions for improving health and safety practices based on their personal experiences. New ideas and or descriptions of incidents, responses, and insights into incident prevention should be sent to the Safety Administrator. These will be posted in a folder titled “Lessons Learned” at the same Winserver location noted above, and incorporated into future HASP revisions, as appropriate .

2.0 ORGANIZATIONAL STRUCTURE

2.1 GSI Company Safety Administrator

The GSI Health and Safety Program , including this plan, is administered by the GSI Safety Administrator. Responsibilities include preparation, distribution and updating of the GSI HASP; coordination of safety and health training and medical monitoring; review of site-specific health and safety plans; investigation of on-the-job accidents, injuries and occupational illnesses, and maintenance of health and safety related records and files. In the event of an on-the-job injury, the GSI Health and Safety Administrator is responsible for making a determination of whether the injury is recordable under OSHA, and is responsible for maintaining the OSHA 200 log, and for filing OSHA Form 101, Supplemental Record of Occupational Injury or Illness.

GROUNDWATER SERVICES, INC.

Robert Lee, GSI Vice President, is the current GSI Health and Safety Administrator. Shawn Paquette, GSI Vice President, is the Health and Safety Co-Administrator. Both may be reached at 713 522-6300, or by cellular phone (Lee: 713-775-7330; Paquette: 713-775-7326.

2.2 Project Safety Officers

Site-specific Site Safety Officers (SSO) will be designated for GSI projects involving field activities. On each project, the Project Safety Officer will be designated by the Project Team Leader, and subject to the approval of the Safety Administrator. The SSO must be a qualified person, with knowledge, experience, and training commensurate with the responsibilities for the particular site and project. At a minimum, the 40-hour OSHA HAZWOPER training and 8-hour Supervisor Training required by 29 CFR 1910.120 are required.

The SSO is responsible for communication of project health and safety requirements to project personnel, including subcontractors; conducting project safety meetings; ensuring compliance with the HASP; completing the daily site safety record and related documentation; and for communicating safety-related concerns to the client's on-site safety representative and to the GSI Safety Health and Administrator.

2.3 Employee Responsibilities

All GSI employees are expected to be actively involved in safe work performance. They are expected to take primary responsibility for their own health and safety, and to take all appropriate measures ensure that of their fellow employees, subcontract personnel, and the people working around them. Compliance with all elements of the GSI HASP and project-specific health and safety plans is mandatory. Beyond that, employees are encouraged to seek additional information whenever appropriate and to provide recommendations for the improvement of our safety performance. In the event that a potentially unsafe condition or action is observed, it is the employee's duty to bring that condition to the attention of the appropriate person. It may be necessary at times to remind a co-worker to use the proper procedures or personal protective equipment, to suggest a safer way to perform a task to a project team leader, or to intervene with a co-worker to prevent a potentially unsafe act.

All project-related safety concerns and/or accidents are to be reported immediately to the designated Site Safety Officer. Significant concerns should also be brought to the attention of the GSI Safety Administrator or Co-Administrator, either directly by the employee, or through the SSO. Reportable safety concerns include, but are not limited to unsafe physical conditions at the a host facility, unsafe work practices, and "near misses" (i.e., incidents in which, while no accident or injury may have occurred, unsafe conditions or actions result in a narrowly averted accident or injury. Non-project safety concerns and/or accidents (e.g., automobile accidents or safety concerns in the GSI office or warehouse) are to be reported directly to the GSI Safety Administrator. Incident investigation policies and procedures are detailed in Section 3.6.

GROUNDWATER SERVICES, INC.

2.4 Safety Performance Review

GSI employees are evaluated on safety awareness and performance during their annual performance reviews. Employees with a demonstrated awareness of safety and a history of safe work performance will be recognized. Poor safety awareness and performance may be grounds for disciplinary action, possibly including termination for serious or repeated violations of safety policies and procedures.

2.5 Subcontractor Qualification

All subcontractors performing site work for GSI must be prequalified, based on safety performance history. Prior to execution of a subcontract agreement, the subcontractor must complete Exhibit A of the standard GSI Subcontract Agreement "Subcontractor's Safety Program and Performance History." Safety performance history must be updated annually.

In order to perform site work for GSI, the Subcontractor must have a documented Health and Safety Program that meets the requirements of the host facility. In general, the following are minimum performance requirements:

- The OSHA/BLS Recordable Injury Frequency and Lost Work Day Injury Rates must be equal to or less than the average rate for the applicable industry, and

- The Workers' Compensation Experience Modification Rate (EMR) must be less than or equal to 1.0.

More stringent requirements may apply, depending on the requirements of the host facility.

2.6 Coordination of GSI HASP with Site-Specific HASPS

As specified in 29 CFR 1910.120, site-specific health and safety plans (SS-HASPs) must be developed for hazardous waste site operations as defined in that standard. These include cleanup operations (including site investigations) at sites involving hazardous wastes or hazardous substances, directed by federal, state, or local government agencies, including sites governed by RCRA, CERCLA, orders issued by state agencies or administered under voluntary cleanup programs.

Site-specific plans must be available on-site at all times work is being performed. As stated in §1910.120, the site-specific plans do not need to repeat all general information and standard procedures provided in the company's HASP. Accordingly, GSI has developed a standard form for developing site-specific HASPS which reference the GSI HASP. When this form is used, it is also required that a copy of the GSI HASP is also located on-site and available to site workers.

GROUNDWATER SERVICES, INC.

3.0 GENERAL HEALTH AND SAFETY PROCEDURES

3.1 General Practices

All GSI employees and subcontractors are expected to work in a manner to protect the environment and the health and safety of themselves and those around them. Specific procedures will be detailed in site-specific health and safety plans prepared for each project. However, the following guidelines apply to all projects at all locations.

3.1.1 Orientation

All new employees will be provided an orientation to the GSI HASP prior to any on-site project work. An orientation will also be given to the site-specific HASP for each project. New employees will spend a minimum of two weeks working under the direct supervision of an experienced GSI employee, and will be overseen in the performance of new tasks for a longer period as needed.

3.1.2 Host Facility Requirements

Health and safety requirements of host facilities at which GSI projects are being conducted will be strictly observed. These may be presented in an orientation conducted at the site or in a contractor safety manual. In some cases, these requirements may differ from GSI standard health and safety standards. In such cases, the more protective standard will apply.

3.1.3 Buddy System

GSI employees will employ the “buddy system” during field operations. Typically, two or more employees will be assigned to field tasks, or a GSI employee may be accompanied by subcontract personnel or client contact. Plant and unit sign-in and sign-out procedures will be observed, and in some cases, radio contact with a plant control room may be required and may substitute for the physical presence of a “buddy.” Some low-risk tasks, such as measurement of water levels or routine inspections in high visibility areas, may be safely performed by an individual working alone. This determination will be made by the Project Team Leader or Site Safety Officer.

3.1.4 House-Keeping and Inspection

All work areas should be kept neat and free of debris which may pose a trip hazard or otherwise interfere with the safe performance of the work. The work-site should be inspected at the end of each day and prepared for the following day’s activities. At the termination of the project, the site should be left free of debris or surplus materials. The work site shall be inspected daily by the Site Safety Officer of designee to ensure it the area is free of potential hazards, including, but not limited to slip/trip hazards, potential falling object hazards, and chemical exposure.

3.1.5 Tool Inspection and Use

GSI provides tools for projects, including hand tools, electrically-powered tools, and other powered equipment with moving parts such as cement mixers, gasoline-powered generators and pumps. All tools must be inspected prior to use by the person using them. Tools which are not in proper repair pose a hazard and should not be used.

Electrical tools must be either double–insulated or grounded. Power tools and extension cords which have had the grounding plug removed, or which have damaged insulation exposing the electrical wires must not be used. Electrical tools designed to accommodate guards must have guards in place to protect against accidental contact with moving parts, such as saw-blades, belts, drive chains fly wheels, and pulleys. Eye protection must always be worn when using cutting drilling, chipping, or other tools, which could result in discharge of small particles to the air.

Hot-work permits must be obtained as required by the host facility for operation of sparking equipment in designated areas.

3.1.6 Personal Protective Equipment

On all GSI projects, the minimum required Level D personal protective equipment PPE will include the following: hard hat, safety glasses with side-shields, steel-toed safety shoes or boots, long pants, and shirt with sleeves. Additional PPE required for specific tasks or locations will be specified in site-specific health and safety plans, and may include various types of gloves, hearing protection, chemical-protective clothing, fire-retardant clothing, or respiratory-protective equipment. GSI will provide employees with all necessary PPE. Each employee engaged in field activities will be furnished with a hard hat, safety glasses (prescription if needed), steel toed boots, and air-purifying respirators, for their exclusive use, and will be responsible for maintaining the equipment and arranging for replacement when needed. Disposable equipment will be furnished as needed. The PPE and respiratory protection programs are presented in Sections 5 and 6. PPE must be inspected daily by the user. In addition, the Site safety Officer or designee shall inspect the PPE in use by the work crew and ensure that the proper PPE is in use and is in good working order.

3.1.7 First-Aid

First-aid kits are carried on GSI field vehicles, including rental trucks, and are available in the office and warehouse spaces. The first aid-kit should be inspected prior to project mobilization to ensure it is complete. The kits are equipped for responding to minor injuries such as cuts and scratches. In the event of more serious injuries, aid from properly qualified personnel should be sought, by contacting emergency response providers at a host facility, visiting a hospital emergency room, or by calling 9-1-1.

3.1.8 Fire Protection

GSI employees must observe all host-facility requirements regarding hot-work permits and restrictions on the use of spark-producing equipment such as gasoline-powered engines. Gasoline for use in pumps or other powered equipment must be transported in designated, labeled cans with self-venting, spring-activated lids and flame arresters. Fire-extinguishers are carried on all GSI field vehicles, including rental trucks, and should be placed in an accessible area close to spark-producing equipment.

At the GSI warehouse, flammable and combustible materials must be stored in the appropriate cabinet, which must be closed at all times when not in use. Fire extinguishers are available in the GSI office and warehouse facilities in clearly marked locations.

Smoking is not permitted in any GSI facility, including the office or warehouse, or in GSI vehicles, including rental vehicles, or on job sites, except in designated smoking areas. All host-facility restrictions on possession of smoking materials, matches or lighters must be observed.

3.1.9 Emergency Response

Emergency response procedures, including emergency reporting, will typically be specified by host facilities, and must be followed, including site-specific procedures for notifying emergency response personnel when an emergency is detected. In general, GSI employees are not trained as first responders to emergencies and, unless they have received specific training, should not attempt to perform emergency shut-down, spill abatement, or fire-fighting in cases involving a significant risk of injury or chemical exposure.

Generally, the occurrence of a fire or chemical release on a facility will be signaled by a site-specific alarm, such as a horn or whistle. The site-specific orientation provided by the host facility will typically specify the codes for emergencies in various areas and designate an assembly point. Unless otherwise directed by the host facility, in the event of a fire or chemical release to the air, all powered equipment, including vehicles, should be shut down and the keys left in the vehicle. The project team leader or site safety officer should account for all project personnel on-site. The wind direction relative to the release should be noted and personnel should move upwind or cross-wind to a designated assembly area. In the event of fire, unless they have received specific training, employees should not attempt to extinguish the blaze if it places the individual at risk.

In the GSI offices, the emergency procedures specified by the building management will be observed. These are specified in the building Life Safety Plan, a copy of which is included in the GSI Employee Manual. Unless otherwise directed, the building should be exited by proceeding in orderly fashion down the stairs at either end of the building.

3.1.10 Prohibited Items and Restricted Activities

GSI policy prohibits the possession and or use of illegal drugs and alcohol and other controlled substances in the work place, including GSI's facilities and our clients' facilities, and in vehicles owned or rented by GSI. GSI employees may not consume alcoholic beverages during the lunch hour, or during any other break, if they will subsequently be going to a job-site, or operating a company vehicle or other equipment. The substance abuse policy is discussed in Section 7 and the substance abuse program is presented in Appendix A.

In addition, GSI prohibits the possession and or use of firearms or other weapons, fireworks or explosives, or other items which could be used as such, in the workplace, including GSI and client's facilities. When working on a client's facility, GSI employees must also comply with our client's policies and procedures, which may include prohibitions on such activities as smoking, carrying smoking materials such as cigarettes, matches and lighters onto the facility, radio playing, card playing, reading of newspapers or magazines.

Work-place violence, including fighting and or the making of explicit or implicit threats against any person, is absolutely prohibited and will be grounds for immediate dismissal.

3.1.11 Environmental Compliance

GSI employees are required to abide by all applicable federal, state, and local environmental regulations and our clients' requirements regarding protection of the environment. This includes, but is not limited to, proper management of wastes derived from site investigations or remedial activities such as soil drill cuttings, purged groundwater, and contaminated equipment, preventing spills and discharges, and properly responding to accidental releases. All regulated materials must be managed in a manner appropriate to the material and site, as specified in the project workplan or client's procedures.

Spill containment kits, including sorbent materials, containers, and handling equipment (e.g., shovels) should be available on-site for projects involving potential for release of regulated chemicals or wastes. On projects where groundwater containing hazardous constituents or hazardous waste is being managed, the CERCLA reportable quantities of the specific substances should be specified in the workplan and an attempt made to quantify the volume of released material.

In the event of an accidental spill, project–specific response actions, including containment or abatement and reporting must be followed. Unless otherwise directed, a spill should be reported as soon as possible to the SSO, who will then report to the designated client contact and GSI Safety Administrator.

3.2 Heat Stress/Cold Exposure

3.2.1 Heat Stress and Sun Exposure

Heat stress can be a major hazard during much of the year in southern climes, particularly for workers wearing personal protective equipment (PPE). The material that protects worker from chemical hazards can also evaporation of perspiration and prevent dissipation of body heat. In addition, the use of PPE increases energy expenditure to perform a given task. Depending on the ambient temperature, physical condition of the individual, and work conditions, heat stress can occur very rapidly (within 15 minutes). Excessive sun exposure, particularly on the arms, face, and neck, can contribute to skin damage.

The major varieties of heat-related disorders, their related symptoms and appropriate treatment are listed below in order of increasing severity.

Condition & Related Symptoms	Heat Stress	Heat Exhaustion or Heat Syncope	Heat Stroke
Cramping	May be present	May be present	Absent
Mental State	Faint, dizzy, fatigue	May be disoriented	Stupor or coma
Skin & Complexion	Cool, moist, flush; rash may be present.	Cool, pale, moist	Red, hot, dry
Temperature	Normal	Normal to low	Very high (>105° F)
Pulse	Rapid (>110 beat /min)	Rapid, weak	Rapid, bounding
Blood Pressure	May be low	May be low	May be high in early stages

Treatment	Give water & electrolytes, loosen or remove clothing, move to shade	Give water & electrolytes, loosen or remove clothing, move to shade	Provide rapid cooling by immersion; cover in wet cloth and transport to emergency room

Prevention Measures: All heat disorders are caused by loss of fluids and the body's inability to cool itself. Heat stress is preventable. The following measures should be taken by all workers:

- Maintain a general level of good health and physical fitness.
- Pre-hydrate before going into the field: water or water-electrolyte drinks are preferable to caffeinated beverages or soft drinks. Refrain from alcohol the night before field work.
- While in the field drink frequently. Numerous small drinks at a tepid temperature are better than rapid, large volume intakes of iced drinks.
- Be aware of warning signs such as fatigue, dizziness, faintness or light-headedness, disorientation and report the on-set of symptoms to your supervisor.
- Do not over exert and rest at least a few minutes every hour or two, or more frequently in warm weather.
- Monitor co-workers for signs of heat stress, such as altered complexion, clumsiness or stumbling, or apparent disorientation, and bring their occurrence to the attention of the individual and their supervisor if symptoms appear.

In addition, the SSO should take the following measures:

- Plan the job to prevent heat exposure: to the extent feasible, schedule tasks to take advantage of available shade (e.g., work on the west side of a structure in the AM and on the east side in the PM).
- Try to schedule work so that the most strenuous tasks are not performed during the hottest part of the day.
- Devise a work schedule that provides sufficient time for re-hydration, rest, and heat dissipation and ensure that workers comply.
- Provide sun screen to protect workers from excessive sun exposure.
- Ensure an adequate supply of drinking water is provided.
- Provide a shaded rest area and consider use of fans.
- Monitor workers for signs of heat stress or exhaustion and intervene if they appear to be over-exerting.

3.2.2 Cold Exposure

Cold injuries (including frostbite and hypothermia) and impaired ability to work are two dangers caused by extremely cold conditions. Warning signals include reduced coordination, drowsiness, impaired judgment, fatigue, and numbing of toes and fingers. Cold exposure can be prevented by appropriate clothing for cold weather work, providing for warm shelter at the work site, and monitoring each worker's physical condition.

3.3 Drilling, Excavation, and Other Heavy Equipment Operations

GSI routinely utilizes the services of subcontract well drillers and other subcontractors supplying equipment and operators for excavation during remediation or construction

activities. Special care must be taken to avoid accidents and injuries on projects entailing heavy equipment operations.

3.3.1 Underground and Overhead Utilities Clearance

Prior to any operations involving drilling, subsurface probing, or excavation, drilling or digging locations must be cleared for underground utilities. For most refineries, chemical plants and other major industrial facilities, this is generally done through the host facility. For sites on or near public rights-of-way or power line or pipeline easements, clearance is obtained through organizations such as the Texas Excavation Safety System (TESS: call 1-800-DIG-TESS or use the TESS Fax-a-Locate Service 1-800-690-1291). Locations should be clearly marked with stakes and or paint, and a street address or map showing the locations should be provided at least 2 working days in advance of any drilling or excavation. On plants, if feasible, the site should be inspected in the presence of the site representative. The location of overhead power lines should also be noted relative to drilling or excavation locations and a safe distance (at least 20 ft) maintained between power lines and the drillrig mast or excavation equipment.

3.3.2 Operational Safety

Drilling and other equipment must be in good condition, and must be inspected upon arrival on-site Particular attention should be paid to the condition of cables and hoisting equipment. The equipment must be equipped with a back-up beeper. Barricades or caution tape should be used as needed to exclude unauthorized personnel from the work area.

During drilling, the drillrig should be positioned to allow for adequate work room and the area kept free of trip and slip hazards. Care must be taken to avoid the catching of loose clothing in moving parts, and to keep hands free of pinch points. Proper PPE including hard hat, safety glasses, gloves, hearing protection, and safety shoes must be worn.

In the event that it becomes necessary to free a stuck cable from the upper portion of the drillrig mast, the mast should be lowered, rather than climbed, if feasible. If it is necessary to climb the mast to make a repair, a harness should be used for fall prevention. In the event of lightning, operations should be suspended, and the mast should be lowered. The geologist's logging table should be situated to face the driller so that operations can be clearly viewed and communication is facilitated.

Acrylic core tubes used for soil sampling can be difficult to handle while cutting open a significant risk of serious laceration can result. A cradle or jig to hold the tube, and a cutting tool specially designed for the tubes are available and should always be used.

3.3.3 Forklift Operations

GSI periodically rents forklifts for movement of drummed investigation-derived wastes, palletized well construction materials, or other heavy items. Only employees who have been trained in fork-lift operations in accordance with §1910.178(l) are permitted to operate forklifts. Before use the equipment must be inspected to ensure proper function.

3.4 Confined Space and Excavation Safety

GSI's activities do not routinely involve entry of personnel into confined spaces such as tanks, vessels, excavations, etc. In the event that a specific project requires entry into a permit-required confined space, assigned personnel will receive proper training prior to project start-up as described in Section 4.

To avoid possible hazards associated with inadvertent confined space entry, GSI employees must obey all posted restrictions on entry to confined spaces, and are expected to know the defining characteristics of a confined space and an entry-permit required confined space: Four defining features of a confined space include: 1) it is not meant to be continuously occupied by workers; 2) it has limited or restricted openings for entry or exit; 3) it has poor natural ventilation; and 4) its size, shape or use may injure workers entering it. A confined space is a permit-required confined space if any of the four characteristics apply: 1) the atmosphere can become IDLH; 2) there is potential for engulfment; 3) its size or shape can trap or asphyxiate; or 4) any other serious recognized safety hazard is present.

Excavations or trenches deeper than 4 ft should not be entered for any purpose unless 1) the excavation walls are properly shored or are sloped at a 1:1 slope, or less steep, and there is no danger of collapse or engulfment; 2) a suitable means of egress such as ramp, stairs or ladder is located so as to require no more than 25 ft of lateral travel to reach it; and 3) testing demonstrates a hazardous atmosphere is not present.

3.5 Chemical Hazards

Hazardous chemicals, including organic and inorganic substances may be present on GSI work-sites as process–related chemicals, managed or uncontrolled wastes, or as residues or contaminants in environmental media. Exposure to elevated levels of hazardous substances can result in injury or illness. Potential routes of entry into the body include 1) inhalation of vapors 2) ingestion of dust, 3) absorption through the skin or eyes, or 4) injection into the bloodstream via a cut, puncture or other wound. Precautions must be taken to prevent exposure to unsafe levels of hazardous chemicals.

The site-specific HASP must identify the hazardous chemicals known or suspected to be present at the site chemicals, and identify their harmful properties and applicable exposure limits. The mode of occurrence in the environment (e.g., sorbed to soil and/or dissolved or as free-phase, in or groundwater), and their known or expected concentrations, based on existing site data, if available, should also be described. As detailed in the Hazard Communication Plan (Appendix C) Material Safety Data Sheets (MSDS) limits should be obtained for the constituents of concern (COCs) and reviewed to ensure an understanding of the nature of the hazard associated with each COC and hazard avoidance measures including for applicable exposure pathways, permissible exposure limits, and proper identification and use of personal protective equipment. The MSDSs for the primary COCs should be attached to the SS HASP and available on-site.

3.6 Reporting of Safety Concerns and Incident/Accident Investigation

GSI employees are required to report unsafe conditions or activities, and are encouraged to provide recommendations for the upgrade of safety practices. All project-related

safety concerns and/or accidents are to be reported immediately to the designated Project Safety Officer or acting designee, who will in turn, report them to the designated client representative and GSI Safety Administrator. In addition to more serious injuries and accidents, reportable safety concerns include, but are not limited to, unsafe physical conditions at the a host facility, unsafe work practices, minor injuries requiring first-aid, and “near misses” (i.e., incidents in which, while no accident or injury may have occurred, an unsafe condition or action resulted in a narrowly averted accident or injury).

Non-project safety concerns and/or accidents (e.g., automobile accidents or safety concerns in the GSI office or warehouse) are to be reported directly to the GSI Safety Administrator.

Injuries and illnesses meeting the criteria for recordable incidents will be recorded on the OSHA 200 Log in accordance with the instructions included on the OSHA 200 form. OSHA Form 101, Supplemental Report of Occupational Injury or Illness will also be completed for all recordable incidents. As required by law, the OSHA 200 log for the most recently completed year is posted in a visible location at the GSI office from February 1 to March 1. OSHA 200 logs and Form 101 are kept on file in the office of the Safety Administrator for a minimum of 5 years as required by law.

All accidents or other safety-related incidents will be investigated by the GSI Safety Administrator or his designee, and will include participation by participants, witnesses, and other personnel, as appropriate. If an incident occurs on a host facility, the investigation will be conducted in accordance with the requirements of host facility as well as with GSI practice. Incident/accident reports will be based on interviews with all persons directly or indirectly involved in the incident and with all eye-witnesses, if any. The report will include a description of events, an analysis of the immediate and root causes of the incident, and recommended action items for prevention of recurrence or similar occurrences. Copies of the reports will be kept on file at GSI offices and will be made available to the host facility owner, if applicable.

4.0 HEALTH AND SAFETY TRAINING PROGRAM

4.1 OSHA “HAZWOPER” Safety Training

All GSI field personnel whose jobs require field work on sites with potential exposure to hazardous chemicals are required to complete a 40-hour training course on safety and health on hazardous waste operations and emergency response (Hazwoper), and an annual 8-hour refresher course as required by 29 CFR 1910.120. Key elements of the course include:

- Hazard identification and emergency response;
- Air quality monitoring techniques;
- Proper selection, use, and maintenance of personal protective equipment, including respiratory protection; and
- Decontamination procedures.

GROUNDWATER SERVICES, INC.

All field personnel who perform work in a supervisory role, including directing the activities of subcontract personnel will also complete the 8-hour supervisors training specified by 29 CFR 1910.120.

GSI requires that its subcontractors whose tasks involve potential exposure to hazardous materials also receive the 40-hours training and 8-hour refresher courses as required.

Field workers shall receive a minimum of 24 hours of on the job field training under the direct supervision of the safety officer or other qualified person. Additional training shall be provided as specified in the site-specific health and safety plans.

4.2 Safety Meetings

Company-wide safety meetings to review the HASP for field personnel shall be held at least every six months, typically in conjunction with the OSHA HAZOPER Refresher training which is conducted in-house at GSI's office, twice annually. Additional safety briefings will be conducted at periodic staff meetings (typically on a monthly to bi-monthly basis. Memoranda or emails will be periodically sent to all staff to call attention to specific safety concerns or procedures.

Project safety orientation meetings for GSI employees and subcontractors shall be conducted prior to project start-up. Informal "tailgate" safety meetings shall be held weekly, or at more frequent intervals as project tasks, personnel, or site conditions change. Safety meeting attendance and topics will be documented on appropriate safety forms.

4.3 Hazard Communication "HAZCOM" Program

GSI has implemented a Hazard Communication (Hazcom) Program in conformance with 29 CFR §1910.1200. This program is presented in Attachment C to this Plan. All GSI employees are oriented to the program upon employment. Refresher classes are conducted annually for all employees, in conjunction with the in-house OSHA HAZWOPER Refresher class. The key elements of the Hazcom program are summarized below.

Material Safety Data Sheets (MSDS) are required for all hazardous materials used in the shop or field. The person purchasing or authorizing the purchase of any chemical has the responsibility to obtain an MSDS from the manufacturer or vendor of the chemical and to provide it to the Safety Administrator.

The Safety Administrator is responsible for maintaining a file of all MSDSs at the GSI main office and shop for the use of employees handling the materials. The Safety Administrator is responsible for maintaining an inventory of all chemicals used in the office, shop, or field.

Hazardous materials used by GSI shall be properly labeled, handled, and stored in accordance with the manufacturer's instructions. Flammable materials shall be kept in a closed metal cabinet equipped with a sign clearly indicating its contents.

To the extent feasible, MSDS shall be obtained for hazardous materials which may be present in the soil, groundwater, or other media at particular sites where drilling, sampling, or excavating shall occur. These MSDSs shall be included as attachments to site-specific health and safety plans, and shall be on file at the project field office, where applicable.

When feasible, the primary source for these MSDS should be the host facility owner. Secondary source include published references such as the Chemical Hazard Response Information System (CHRIS) Manuals, compiled by the U.S. Coast Guard. Copies of the CHRIS Manuals are available in the GSI library.

4.4 Energy Isolation (Lock-out/Tag-out) Program

GSI has developed an energy isolation (Lock-out/Tag-out) program to prevent the accidental exposure to hazardous energy. This program is included as Appendix D to the GSI HASP. Host facilities may have additional requirements. Use of lock-out and tag-out procedures is typically limited to groundwater pump and treat or other remediation systems installed, operated and / or maintained by GSI. Detailed training in lock-out/tag-out procedures will be provided to all employees engaged in tasks requiring energy isolation, and lock-out devices will be assigned to them. All employees are required to be familiar with and abide by general lock-out-tag out principles and procedures as described in the GSI plan.

4.5 Site-Specific Training

Most GSI projects will require site-specific training, which may be supplied on-site directly by the site owner, or through a designated local organization such as Houston Area Contractor Safety Council (HACSC) or Contractor Safety Council of Texas City (CSC/TC). Many sites will also require general worker safety training and certification as offered by the local safety council. Entry onto safety council member facilities and site-specific training provided by contractor safety councils also requires a one-day “Basic Plus” class on general safe-work practices, and all GSI field staff are provided with this training as needed for entry. GSI project team leaders are responsible for coordinating with the site owner or designated representative to ensure that all personnel (including subcontractors) receive required site-specific training.

4.6 Confined Space Entry Training

GSI’s activities do not routinely involve entry of perennial into confined spaces such as tanks, vessels, excavations, etc. GSI employees and subcontractors are prohibited from confined space entry unless properly trained and authorized. On most facilities, entry-permit-required confined spaces are posted. However, employees must be familiar with the general characteristics of such spaces in order to recognize the potential hazards, which potentially include low-oxygen, hazardous atmosphere, and/or the potential for engulfment.

The four key features of a confined space are i) it is not meant for continuous occupation by workers, ii) it has limited or restricted openings for entry and exit, iii) it has naturally poor ventilation, and iv) its size, shape or use may injure workers entering it. A confined space becomes a “permit required” confined space when any of the following conditions

apply: i) atmosphere can become IDLH (immediately dangerous to life or health, ii) there is potential for engulfment, iii) the shape or size can entrap or asphyxiate, or iv) any other serious safety hazard is recognized.

In the event that a specific project requires entry into a entry permit required confined space, assigned personnel will receive proper training prior to project start-up. Training in accordance with OSHA requirements will be provided through a qualified organization such as a contractor safety council.

4.7 Other Specialized Training

Additional training may be required and will be supplied for personnel involved in certain other activities as required by specific projects. Examples include training for scaffold safety and forklift operation. Training in accordance with OSHA requirements will be provided through a qualified organization such as local contractor safety councils.

5.0 PERSONAL PROTECTIVE EQUIPMENT PROGRAM

5.1 PPE Selection and Use

5.1.1 General

Selection of personal protective equipment (PPE) shall be based on the tasks to be performed and the potential for worker exposure to the hazards identified during the site evaluation phase of the work program, and must always meet or exceed the host facility's minimum requirements. PPE requirements shall be selected or approved by the project safety officer, and detailed in the site-specific health and safety plan. GSI will provide all necessary PPE to its employees at GSI's expense. All PPE is to be used and maintained in accordance with the manufacturer's instructions.

In general, field tasks require a minimum of Level D protection which shall consist of body covering, including long pants, shirt with sleeves, steel-toed boots; hard hat, and safety glasses with side shields. Protective gloves are to be worn when handling abrasive or sharp materials or chemical substances. Basic Level D PPE will be augmented as appropriate to job or site conditions. The project safety officer is responsible for specifying PPE in the site-specific health and safety plan. The following guidelines should be observed.

5.1.2 Respiratory Protection

The GSI Respiratory Protection Program is presented in Section 6.0.

5.1.3 Hand and Body Covering

Disposable, chemical-resistant coveralls made of Tyvek other equivalent material should be worn during tasks involving potential contact with contaminated soils or other materials, e.g., soil sampling. Poly-coat Tyvek or equivalent should be worn when there is a potential for splashing with free-phase chemical liquids or water with elevated concentrations of dissolved hazardous constituents, e.g., during well development. Other special equipment, such as rubber aprons or slickers should be worn whenever acids or other corrosive or caustic materials are in use as during well development

operations. Flame retardant clothing (FRC) or Nomex must be worn as required by host facilities.

Gloves shall be selected for resistance to the anticipated chemical hazards. At a minimum, an inner, latex or vinyl surgical-type glove should always be worn when there is any potential exposure to chemicals. Additional layers of surgical gloves may be worn when potential for chemical exposure is low and when dexterity is required, (e.g., during soil core logging). When the potential for chemical exposure is greater, gloves of nitrile, neoprene, or other chemical-resistant material should be worn over the inner gloves. Coverall cuffs shall be taped to gloves and boots, as appropriate to prevent skin exposure to hazardous liquids.

5.1.4 Head Protection

Hard hats meeting ANSI Z89.1-1986 standards must be worn in areas where vertical clearance is limited, when there is potential for falling objects or other impacts, and during all operations involving heavy equipment.

5.1.5 Eye and Face Protection

Safety glasses with side shields meeting ANSI Z87.1-1989 standards should be augmented with chemical protective goggles on sites where there is potential for chemical exposure. Face shields are required during operations with potential for splashing or spraying with chemicals or contaminated water, such as well acidification or pressure washing of contaminated equipment, and during operations involving the use of grinders or similar equipment.

5.1.6 Hearing Protection

During operations involving elevated noise levels and/or operations located in areas where noise levels may be high, hearing protection shall be worn. Hearing protection must be worn in areas of host facilities designated as high noise areas or hearing conservation areas. Hearing protection devices must be used during work around drilling rigs, excavation equipment, gasoline or diesel-powered pumps and generators, and other high noise equipment, and in designated areas of GSI customer properties. Acceptable devices include earplugs and ear muffs.

5.1.7 Foot Protection

Steel-toed boots made of rubber, PVC, or other chemical resistant material should be worn whenever there is potential exposure to liquid chemicals or non-aqueous phase liquids. Leather boots are acceptable if no significant potential exists for chemical contamination. Rubber boot covers may be worn over leather boots to prevent chemical exposure.

5.1.8 Hand Protection

Employees are required to wear gloves when hands are exposed to hazards such as chemical absorption by the skin, chemical or thermal burns, serious cuts, abrasions, lacerations or punctures. The compatibility of the glove material with the potential chemical or other hazard must be confirmed when preparing the site-specific HASP.

5.2 Inspection, Decontamination, Maintenance, and Storage

Employees are responsible for ensuring that the PPE issued to them is in proper working order. Non-disposable PPE (e.g. respirators, hard hats, etc.) will be inspected by the employee prior to each use, and will be properly decontaminated, stored and maintained. GSI will provide replacement equipment as needed, but it is the responsibility of the employee to inspect the equipment and request replacement as needed.

5.3 Training

Training in the selection, use, and maintenance of PPE will be conducted as part of the 40-hour OSHA Hazwoper training and annual refresher course specified in Section 4.1, above. Initial training may also be provided through contractor safety councils. Additional refresher sessions will be conducted as needed during site-specific orientation sessions.

6.0 RESPIRATORY PROTECTION PROGRAM

The respiratory system offers a significant potential entry point to the body for many organic and inorganic toxic substances via inhalation of dust, fumes, vapors and mists. In addition, the presence of air contaminants can result in an oxygen deficient IDLH condition. To prevent injury or disease of the respiratory system or asphyxiation, GSI has implemented a respiratory protection program which incorporates monitoring, engineering control measures, and use of respiratory protective equipment in.

6.1 Air Monitoring

Identification and quantification of airborne chemicals is required to ensure worker safety. The goals of the air monitoring program are to:

- Determine the level of personal protective equipment that is required;
- Define areas where controls or respiratory protection is necessary; and
- Determine whether exposure potential may indicate the need for medical monitoring.

A description of the instruments and monitoring procedures and the mechanism for using air monitoring information are provided below.

6.1.1 Air Monitoring Techniques and Instruments

Identification and quantification of airborne contaminants is achieved by using direct reading instruments or chemical detection methods. Depending on the nature of the site, these tools are either used alone or in combination. Three primary air monitoring devices are described below:

Organic Vapor Analyzer (OVA Meter)

- Hazard Monitored: Organic gases and vapors.
- Information Provided: On-site detection and quantification of organic gases and vapors.

- Primary use: Continuous or periodic on-site air monitoring for total airborne organics. Indicates if action level is exceeded, necessitating an upgrade in personal protective equipment or a modification of work procedures.
- Detection Method: Flame ionization detector. Gases and vapors are ionized in a flame, producing a current proportional to the number of carbon atoms present.
- Limitations: Does not detect inorganic gases or vapors. Does not identify specific organic compounds.
- Care and maintenance: Requires charged battery, fuel supply, and periodic calibration.

Draeger Tubes

- Hazard Monitored: Specific organic gases and vapors.
- Information Provided: On-site and rapid identification and quantification of specific gases and vapors.
- Primary use: Identification and limited quantification of specific organic constituents at job site.
- Detection Method: Chemical reaction in indicator tube, producing a stain whose length is proportional to the compound's concentration.
- Limitations: Relatively low precision and accuracy. Some interferences can cause misleading results.
- Care and maintenance: Requires fresh indictor tubes.

Chemical Exposure Badges

- Hazard Monitored: Specific organic gases and vapors.
- Information Provided: Average concentrations of specific gases and vapors over an extended period of time.
- Primary use: Monitors average exposure of worker over an extended work period (days or weeks).
- Detection Method: If exposure occurs, chemical is adsorbed onto badge. Time-weighted average concentration of chemical is determined by laboratory analysis of chemical mass and knowledge of total exposure duration.
- Limitations: Relatively low precision and accuracy; extended time period before results are available limits use to relatively long-term exposure evaluation.
- Care and maintenance: Requires fresh indicator badges, proper badge handling and chain-of-custody procedures.

6.1.2 Utilization of Air Monitoring Information

Air monitoring information is compared against designated action levels to determine the level of personal protective equipment that is required. Action levels are developed in the site specific safety plan based on the following considerations:

- Anticipated or suspected gases and vapors at the site;
- Concentrations of hazardous substances expected in environmental media (e.g., soil or water samples);
- Relative concentration and volatility of components in chemical mixtures;
- Toxicity characteristics of the gases and vapors of concern;
- Warning properties of the gases and vapors of concern; and

- Potential exposure of workers during each phase of the work program.

When monitoring for action levels, a conservative assumption is frequently made that all detected vapors represent the specific chemical of concern (COC) with the lowest permissible exposure limit. Unless more specific information is available concerning the contaminant mixture, this is a reasonable assumption. However, this may result in unnecessary use of respiratory equipment which can increase physical stress on the worker, and so should be avoided, especially in hot weather conditions. The action level may be adjusted based on prior sampling data which indicates the relative proportions of various COCs and their properties such as volatility, toxicity, etc. In setting an action level, the goal should be to ensure that workers are not exposed to COC concentrations exceeding permissible exposure levels without respiratory protection, while at the same time not triggering unnecessary respirator use.

If sustained elevated concentrations above the action level specified in the site-specific health and safety plan are detected in the breathing zone (for a period of time specified in the site-specific health and safety plan) by the OVA meter, or if Draeger Tube analyses indicate concentrations above the designated action level, controls must be implemented or personal protective equipment must upgraded as designated in the site specific safety plan to provide adequate worker protection for the chemical of concern. Otherwise, field work must be suspended or modified to reduce potential exposure to the chemical of concern.

The procedure described above is a general approach which is applicable to common volatile organic compounds encountered in the field. However, a site-specific air monitoring program must be developed for each project based upon the conditions anticipated or encountered at the field location.

6.2 Engineering Controls

The use of respiratory protective equipment such as air-purifying respirators places stress on the body, especially during physical labor performed in hot weather and while wearing protective clothing. In addition, respirators may make verbal communication more difficult, especially in high noise areas. Therefore, whenever feasible, engineering controls and work practice adjustments should be used to reduce exposure to air-borne contaminants. In some cases, a simple adjustment, such as maintaining a position upwind of the contaminant source may be all that is needed to prevent inhalation of air-borne contaminants. Use of fans should also be considered to move vapors away from the workers breathing zone. In some cases, plastic sheeting or other coverings may be placed over affected soil or waste to minimize volatilization to the breathing zone.

6.3 Respiratory Protective Equipment

Use of air-purifying (Level C PPE) or supplied air respirators (Level B PPE) will be based on air quality monitoring as specified in the site-specific health and safety plan. Respirators meeting applicable American National Standards Institute (ANSI) standards shall be provided by GSI and used in accordance with the manufacturer's instructions. Employees will be issued their own respirators for their exclusive use and will be responsible for keeping them clean and in good working order.

GROUNDWATER SERVICES, INC.

6.3.1 Fitness for Use of Respirators

Employees must demonstrate annually that they are it to wear a respirator by successfully passing a pulmonary function test, administered as part of the medical monitoring program (see Section 7.0, below), and obtaining a physician's written opinion that the employee is fit to use a respirator. More frequent pulmonary function testing may be required depending on the employee's medical history. If, based on the pulmonary function test or other factors, the physician's written opinion indicates that the individual is not fit to wear a negative-pressure air-purifying respirator, use of a positive pressure device may be specified instead.

6.3.2 Approved Devices

Air-Purifying Respirators. Air-purifying respirators (Level C PPE), will be based on air quality monitoring as specified in the site-specific health and safety plan. Respirators approved by the American National Standards Institute (ANSI) shall be provided by GSI and used in accordance with the manufacturer's instructions. Air-purifying respirators may not be used in oxygen deficient or other IDLH environments.

All employees who will wear respirators will receive training in their use and must be judged fit to use a respirator based on an annual medical examination which includes a pulmonary function test. Workers must have passed a quantitative respirator fit test for the specific make and model respirator (Section 6.4, below). Fit testing is conducted annually. Selection of a full or half-face respirator or powered air-purifying respirator equipped with the appropriate cartridge shall be based on the chemical hazards identified during site evaluation and atmospheric concentrations measured during the air monitoring program. Positive and negative pressure tests shall be performed to ascertain a proper fit.

Half-face mask and full-face piece respirators are issued to all field personnel. Half-mask respirators typically have an assigned protection factor (APF) of 10, meaning they should not be used if the contaminant concentration in air is 10 times the permissible exposure level of the constituent of concern. Full-face piece respirators typically have an APF of 50. Therefore, if the COC concentration in air is close to or above 10 times the PEL, a full-face respirator should be used, and in the event that the COC concentration approaches 50 times the PEL, supplied air should be specified. As a conservative measure, the site-specific plan should generally specify more conservative action levels corresponding to between 0.5 and 0.8 times the APF to allow for uncertainty regarding the composition of the air contaminant mixture. Some COCs may be particularly irritating to the eyes even at concentrations for which half-mask respirators are fully protective of the respiratory tract. In such cases full-face piece respirators are more appropriate.

Appropriate cartridges must be specified, based on the composition of the contaminant mixture. The cartridges must be used in accordance with the manufacturer's instructions including compliance with the specified service life. Typical service life does not exceed 8 hours from opening of the sealed package and may be shorter in the event of high humidity or elevated contaminant concentration.

Supplied Air Respirators. Use of supplied air (Level B PPE), when performed, will utilize equipment from a supplier meeting all applicable guidelines. The equipment will consist of an approved source of breathing-air, airlines, properly designed face pieces

GROUNDWATER SERVICES, INC.

and a 5-minute escape bottle The equipment will be inspected thoroughly before use by the project safety officer or other qualified person, and procedures for use will be reviewed with project personnel prior to project start-up.

At a minimum, supplied air will be certified to conform to Grade D breathing air specifications per ANSI/Compressed Gas Association Commodity Specification for Air G-7.1-1989, (see 29 CFR §1910.134(i)) and to be provided in containers meeting DOT Container Specification Regulations.

6.3.3 Training

Training in the selection, use, and maintenance of PPE will be conducted as part of the 40-hour OSHA Hazwoper training and annual refreshers course specified in Section 4.1, above. Initial training may also be provided through contractor safety councils. Additional refresher sessions will be conducted as needed during site-specific orientation sessions and the 8-hour OSHA HAZWOPER refresher course..

6.3.4 Fit-Testing

All field employees shall have a passed a quantitative respirator test for the make and model of respirator they will be using. Tests will be performed annually by a qualified analyst under applicable OSHA guidelines. To ensure a proper fit, facial hair in the area of the seal must be shaved.

6.3.5 Respirator Use

To don the respirator, the straps are loosened and pulled to the front of the mask so that the mask seal is unobstructed. The face piece is then placed against the face and the straps are pulled over the head and into place. The straps are then lightly tightened sequentially from top to bottom, and then, once the separator is in place, the straps are re-tightened to provide a snug fit to the face without over-tightening to cause discomfort or constriction.

A seal check is then performed by first placing the hands over the cartridges and inhaling. The mask should contract toward the face and no leakage should be felt along the seal. If a leak is detected, the straps are adjusted and the process is repeated until a good seal is obtained. A hand is then placed over the exhalation vent and the wearer exhales. The mask should be pushed away from the face without breaking the seal. Again, if a leak is detected the straps are adjusted and the test is repeated.

During use, if a leak is detected, the wearer should leave the affected area, remove outer gloves, and make adjustments as needed to obtain a good fit. At the end of the use period, the wearer should leave the affected area, remove outer gloves and, retaining the inner gloves, remove the respirator by first loosening the straps and pulling them over the head with one hand while holding the face-piece with the other.

6.3.6 Inspection, Decontamination, Maintenance, and Storage

Respirators will be inspected by the employee prior to each use, and will be properly decontaminated, stored and maintained. Following use, the cartridges should be removed and discarded, the respirator should be cleaned with a suitable disinfectant cleaner, or with mild detergent and warm water solution, thoroughly rinsed in warm clear water,

hand dried with a soft lint-free cloth, and placed in a clean protective casing such as a plastic bag, and stored out of the elements.

Employees are responsible for ensuring that the PPE issued to them is in proper working order. GSI will provide replacement equipment as needed, but it is the responsibility of the employee to inspect the equipment and request replacement as needed.

7.0 MEDICAL SURVEILLANCE

7.1 Applicability

The GSI medical surveillance program is designed to help assess and monitor the health and fitness of all employees who work with hazardous substances. The following employees are required to participate in the program:

- All employees who participate in field work for 30 days per year or greater at sites where hazardous materials are known to be present;
- Workers who are exposed to unexpected or emergency releases of hazardous materials above exposure limits or who show signs, symptoms, or illness that may have resulted from exposure to hazardous substances; and
- Other employees as designated by GSI.

7.2 Elements of Medical Surveillance

A medical exam will be conducted under the supervision of a licensed physician, without cost to the employee, and without loss of pay. The examination is intended specifically to ascertain whether the employee is at any excess risk for chemical exposure, and is fit to use personal protective equipment in general, and respiratory protective equipment in particular, and to assess whether any limitations need to be paced on their use. The physician will conduct the specific tests and procedures necessary to make that determination for each employee. The examination may consist of some or all of the following procedures and analytical tests, some of which are optional:

- A medical and work history;
- General physical examination;
- Blood chemistry;
- Urine analysis;
- Blood temperature and pressure;
- Pulmonary function;
- Chest x-ray;
- Vision test; and

- Hearing test.

GSI will provide the employee with a copy of the results of the examination and any written opinions furnished by the examining physician. Any conditions that may be related to exposure to hazardous substances will be reported immediately to the employee. The physician will not reveal to GSI specific findings, diagnoses, or opinions unrelated to employment.

7.3 Frequency of Medical Examination

The medical examination will be performed according to the following schedule:

- Prior to job assignment;
- Annually after beginning work;
- As deemed necessary by the examining physician;
- As soon as possible for employees injured or becoming ill from exposure to hazardous substances during an emergency, or who develop symptoms of overexposure from hazardous substances; and
- At the termination of employment (if the employee has not had an examination within the last 6 months).

7.4 Records of Medical Examination

Records of medical examination, including the Physician's Written Opinion form are provided by the examining physician to the Safety Administrator under a confidential seal. A copy of the records are provided to the employee and the original is retained in a locked file located in the office of Safety Administrator. Records of medical examinations will be maintained for a period of 30 years.

It is GSI policy that the contents of employees' medical records are confidential and are therefore not examined by the Safety Administrator or other GSI personnel, unless required by specific circumstances. However, the Safety Administrator does review the Physician's Written Opinion form to determine whether any limitations on work assignments or use of personal protective equipment (PPE) are appropriate. If the review of this document indicates that the examining physician has not certified that the employee is fit to wear a respirator, that limitations on the use of PPE are recommended, or that follow-up examination or re-testing is recommended, the employee is so notified, and encouraged to schedule appropriate follow-up as soon as feasible.

7.5 Drugs, Alcohol, and Other Prohibited Items

The GSI policy regarding substance abuse and its prevention is summarized in the "Company Policy Regarding Drugs, Alcohol, and Other Prohibited Items" (see Attachment A). This document presents the GSI company policy regarding substance abuse and provides details regarding the administration of the drug abuse prevention program.

8.0 VEHICLE SAFETY PROGRAM

In order to promote safe driving practices for all employees, GSI has developed a vehicle safety program. A written copy of this program is included as Attachment B.

9.0 RECORD KEEPING

GSI employees will be given a copy of their written medical examination report when a copy of such report is received by GSI. In addition, GSI will retain all medical records on file. OSHA 200 logs and Form 101 will be maintained on file a minimum of 5 years and posted in accordance with the instructions included on the OSHA 200 form. OSHA HAZWOPER training records, respirator fit-test records for each employee are maintained by the Safety Administrator for a minimum of 5 years following termination of employment. Records of medical surveillance are maintained for 30 years.

Daily Site Safety Records and Tailgate Safety Meeting forms must be completed on all field projects and must be placed in the project file. Project safety records will be kept on file for a minimum period of three years following completion of the project.

10.0 SITE-SPECIFIC SAFETY AND HEALTH PROGRAM

10.1 Applicability

Site-specific health and safety plans shall be prepared for 1) projects which require the use of drillrigs, backhoes, or other heavy equipment, 2) projects which require the collection of samples of soil, water, or other media containing potentially harmful concentrations of hazardous materials, and/or 3) projects where site conditions pose a significant risk to human health and safety. Prior to project start-up, the project scope of work and available site data shall be evaluated to determine the specific requirements for a site-specific health and safety plan. It is the responsibility of the Project Team Leader (PTL) to ensure the site-specific HASP is prepared, though the actual preparation may be performed by a designee of the PTL. All site-specific HASPS are subject to review and approval by the SGI Safety Administrator.

The health and safety representative for the host facility will be contacted and a copy of the host facility health and safety plan, contractor health and safety guidelines, or equivalent must be obtained and evaluated in order to incorporate all relevant portions of the host facility plan into the GSI site-specific plan. Review of the GSI site-specific plan by the host facility representative is conducted at the discretion of the host facility project manager or authorized representative. The following paragraphs detail the elements to be addressed by or included in the site-specific health and safety plan.

GROUNDWATER SERVICES, INC.

Site-specific health and safety plans must be kept on-site at all times when work is being conducted and available to all employees and subcontract personnel. Prior to commencement of work, the site-safety officer or other person designated by the project manager or project team leader, will conduct an orientation to the plan for the project field team. All site personnel must sign the coversheet to the plan certifying their understanding of the project health and safety requirements and their agreement to abide by the plan.

As allowed under OSHA regulations (29 CFR 1910.120) the site-specific health and safety plan "need not repeat the employer's standard operating procedures." GSI has developed a site-specific health and safety plan form, provided in Appendix E, which may be used in conjunction with the this plan. The GSI HASP may be referred to for specific procedures for monitoring, selection and use of personal protective equipment, personnel training, and other required elements of the site-specific plan. When used in this manner, a copy of this document must also be on-site with the site-specific plan and available to all site workers.

10.2 Site Evaluation and Job Safety Analysis

For projects requiring a site-specific health and safety plan, a job safety analysis, or JSA, shall be performed in order to provide the information necessary to eliminate or effectively control anticipated health and safety hazards. Available information regarding the presence, use, storage and/or disposal of hazardous materials shall be collected and reviewed. The scope of work shall be reviewed to identify specific tasks which may pose the risk of injury or chemical exposure to project personnel. A reconnaissance shall be performed by the designated project safety officer or other qualified person, as needed to provide information on current site conditions. Critical elements of the site evaluation include:

- Location and size of the site, topography, structures, accessibility, manufacturing or other operations or processes which could affect the safe implementation of the work;

- Suspected presence of conditions immediately dangerous to life and health (IDLH);

- Identification of potential hazards, including physical, chemical, and biological hazards; and

- Location, phone numbers and maps to the nearest emergency medical facilities.

The initial site evaluation must include an assessment of the possible presence of Highly Hazardous Chemicals at quantities above applicable Threshold Quantities identified in 29 CFR §1910.119. The client health and safety representative should be contacted to 1) determine whether such materials are present, 2) obtain material safety data sheets and other appropriate information, and 3) identify and make arrangements for any specific training which may be required for work in and around the unit or area, including procedures in the event of an accidental release of materials to the environment.

10.3 Elements of the Site-Specific Health and Safety Program

The site-specific health and safety plan shall include the following elements. The specific organization of the plan may be varied:

- **Project Description:** An introductory section shall provide a summary of the project objectives, tasks, location and generalized project schedule.

- **Site Description:** The description shall include a physical description of the site and the identification of potential physical, chemical and biological hazards. If feasible, a site map should be included.

- **Emergency Procedures:** Emergency procedures must be specified, including any alarm signals, emergency contact information, location of assembly areas

- **Project Organization, Personnel, and Training:** This section identifies key project personnel, training requirements and other qualifications for site workers.

- **Potential Hazards and Hazard control Measures:** This section identifies potential hazards, including physical and chemical hazards, and measures to mitigate of avoid hazards, including site controls, utility clearance, and safe work practices.

- **Air Quality Monitoring:** This section specifies monitoring instrumentation and methods to prevent exposure to air-borne contaminants.

- **Personal Protective Equipment:** This section specifies basic PPE requirements and conditions for PPE upgrades, including action levels and specifications for use of respiratory protection. \

- **Decontamination:** Procedures for decontamination of personnel and equipment are be specified. Where the possibility of a spill of hazardous materials exists, a list of the equipment to be present on site and the procedures for responding to a spill will be specified in this section.

- **Safety Plan Distribution and Compliance:** GSI requires its employees and subcontractors to read, understand and certify in writing their agreement to comply with all of the rules and regulations contained within the site-specific health and safety plan. Periodic inspection of work sites will be conducted by the Safety Administrator to ensure compliance.

GROUNDWATER
SERVICES, INC.

APPENDIX A

COMPANY POLICY REGARDING DRUGS, ALCOHOL, AND OTHER PROHIBITED ITEMS

GSI Health and Safety Plan

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

GROUNDWATER SERVICES, INC.

APPENDIX A

COMPANY POLICY REGARDING DRUGS, ALCOHOL, AND OTHER PROHIBITED ITEMS

POLICY STATEMENT

Groundwater Services, Inc. (GSI), is committed to maintaining a safe and productive work environment for all employees and to providing efficient services to our clients. We further recognize the deleterious impact of drug and alcohol abuse on work-place safety, employee performance, and absenteeism. Therefore, to ensure a safe work environment, a drug-abuse prevention program will be implemented to:

- Restrict certain items and substances from being brought on or being present on company property;
- Prohibit GSI employees and all others from reporting to work, working, or being present on company property or at the work site while having detectable levels of certain drugs and other substances in their systems;
- Establish routine testing methods to detect such substances or conditions; and
- Provide assistance to those employees requesting counseling or rehabilitation services.

The provisions of this drug-abuse prevention program are detailed below. Note that some GSI clients have additional testing requirements which will apply to employees working n their facilities. In such cases, an alternative or supplemental plan may be specified for those employees working on for specific clients or on specific sites. At present, ExxonMobil is the only GSI client for which a supplemental testing protocol is required. Employees performing work at ExxonMobil facilities must abide by the conditions of the ExxonMobil Model Plan.

Prohibited Items

The use, possession, sale, manufacture, distribution, dispensation, concealment, receipt, transportation, or being under the influence of any of the following items or substances on GSI property by employees and all others is prohibited:

- **Illegal drugs and controlled substances** including, but not limited to marijuana, cocaine, opiates (i.e. morphine and codeine, phencyclidine, amphetamines, methamphetamines), and any other drugs or substances which will in any way affect safety or job performance.
- **Alcoholic beverages**, except at special functions as specifically authorized by GSI management. Consuming alcoholic beverages while driving any vehicle for company business is prohibited. Alcohol may not be consumed during lunch breaks if the employee will subsequently be returning to work on a client's facility.
- **Drug paraphernalia**

- **Over-the-counter medications**, except those which are taken in accordance with manufacturer's dosage recommendation and which do not restrict an individual's work activity.

- **Prescription drugs**, except those which have been prescribed by an authorized medical practitioner for the person in possession of the drugs and which do not restrict the individual's work activity.

Conditions of Testing

GSI employees will be required to submit to a urine drug test, a breath test, and/or a blood test under the following circumstances:

- **Routine Drug Testing:** GSI requires mandatory urine drug testing for all GSI employees on at least an annual basis. This drug testing will be conducted in conjunction with annual physical examination required of all employees. Additional testing may be conducted as required for entry on client property.

- **Reasonable Suspicion:** An employee will be subject to testing for sub-stance use when there is reasonable suspicion that he/she is unable to perform his/her job, or that he/she is under the influence of drugs or alcohol.

- **Pre-Employment:** Offers to prospective employees will be made contingent upon pre-employment urine drug testing and a complete physical examination. Applicants testing positive for drug use will not be hired.

- **Legal or Regulatory Requirements:** Other testing or conditions may be required to comply with local, state, or federal laws, contractual agreements, or regulatory requirements.

- **Client Requirements:** Adoption of drug and alcohol policies or programs of GSI's clients may be required for employees working on specific facilities. GSI clients may require additional testing for entry onto their sites, including random testing upon entry. This may also include inspection and search of vehicles or persons. Employees working on ExxonMobil facilities, must comply with the requirements of the ExxonMobil model Alcohol, Drug, and Contraband Policy in Addendum A.1. Employees working on ExxonMobil sites will be required to sign a form acknowledging their understanding of the policies and consenting to the release of test results. Employees working on Shell facilities are also subject to random testing.

Drugs to be Tested and Levels of Detection

Urine drug tests shall be run by a certified testing laboratory which uses the best available technology for measuring metabolites of substances entering a person's system. Initial drug tests will employ an enzyme immunoassay technique. All specimens identified by the initial test as positive shall be reanalyzed by a gas chromatography/mass spectrometry (GC/MS) technique for confirmation.

All persons shall have the opportunity, prior to testing, to list all prescription and non-prescription drugs they have used in the last thirty days and to explain the circumstances surrounding the use of such drugs.

Samples will be analyzed for the following substances:

Drug Group	Positive Detection Level (ng/l)	
	Initial Test	Confirmation Test
Amphetamine	1000	
Amphetamine		500
Methamphetamine		500
Cocaine metabolites	300	150
Marijuana metabolites	100	15
Opiate metabolites	300	
Morphine		300
Codeine		300
Phencyclidine	25	25

Testing for additional substances, (e.g., for alcohol) may be required for employees assigned to work on specific facilities. Alcohol testing will be performed on breath, saliva or blood, but not urine samples.

The positive detection levels specified above are subject to change as warranted by advances in technology. (Note: The above detection values are expressed in units of nanograms/liter (ng/l) which is roughly equivalent to 1 part per billion.)

ADMINISTRATION OF THE DRUG ABUSE PREVENTION PROGRAM

The GSI drug-abuse prevention program will be administered by the company President or designated officer. Procedures for employee notification, evaluation of test results, data confidentiality, and disciplinary action are as follows:

- **Employee Notification**: GSI will provide written copies of this policy to all employees. Additional information will be made available regarding the impacts of drug abuse on the workplace and the responsibility of employees and their supervisors under this prevention program. Prior to any drug testing, employees will be requested to sign a consent form authorizing performance of the test and permitting the release of test results to company officials. The consent form will set forth the procedures for confirmation of an initial positive test result, the consequences of a confirmed positive test result, the consequences of refusal to consent to such testing, and related employee rights.

GROUNDWATER SERVICES, INC.

- **Evaluation of Test Results:** GSI will appoint a licensed physician with a knowledge of substance abuse disorders to act as Medical Review Officer (MRO). The duties of the MRO will include evaluation of drug testing procedures, interpretation of test results, and discussion with employees regarding the significance of positive test results and possible alternative explanations.

- **Confidentiality:** All information from an employee's or applicant's drug test is confidential and will be disclosed only to company officials with direct responsibility for the drug-abuse prevention program. Disclosure of test results to any other person, agency, or organization is prohibited unless written authorization is obtained from the employee. All records relating to the taking of a drug test or the order to take a drug test shall be deemed confidential unless written authorization has been obtained from the employee or the records become the subject of a judicial proceeding. The results of a positive drug test shall not be released until these results are confirmed. The company shall implement procedures to prevent the unauthorized distribution of such information.

- **Disciplinary Actions:** An employee found in violation of any aspect of this policy, or refusing to submit to drug testing or to sign the appropriate consent and chain-of-custody forms shall be subject to termination or disciplinary probation, at the discretion of the company. A second violation of this policy will result in immediate termination from employment.

  Any employee who is confirmed to test positive for drug or alcohol use for the first time will be given a choice of rehabilitation or termination from employment. Any employee who is confirmed to test positive for drug or alcohol use for a second time will be terminated from employment. Tampering with lab specimens or procedures in any manner will result in immediate termination of employment for all parties involved.

  Any employee who is convicted or pleads guilty or no contest to a legal violation related to drugs or alcohol will be subject to termination and will be required to submit to drug testing prior to returning to work.

EMPLOYEE RIGHTS

The opportunities available to an employee to challenge or explain a confirmed positive drug test will include the right to:

1) meet in private with designated company officials,

2) obtain a portion of the remaining sample to be independently tested at the employee’s expense, and

3) procure a second opinion regarding the test findings by a licensed physician with knowledge of substance abuse disorders at the employee’s expense.

If an explanation of a positive drug test merits further inquiry, for the duration of the inquiry, the employee will be suspended without pay or returned to work, at the discretion of the company.

REHABILITATION

Rehabilitation may be offered at the request of the employee if the request is unrelated to an identification of the employee as a violator of the policy and the violation does not involve selling or distributing drugs or serious misconduct. The costs of rehabilitation will be paid for by the Company only within the limits of the existing medical benefits program provided to that employee.

Rehabilitation may involve professional counseling on an outpatient basis for employees allowed to remain at work or daily outpatient drug maintenance, hospitalization, or detoxification for employees suspended from work. The company will provide the employee with relevant information, such as the identity of local community resources for the treatment of substance abuse disorders.

Any employee who accepts rehabilitation approved by the company, but fails to complete the prescribed program or to comply with the prescribed after-care, is subject to termination. Upon successful completion of the recommended rehabilitation, the employee will be tested before returning to work. After returning to work, the employee will be subject to periodic drug or alcohol tests until deemed recovered by the Medical Review Officer.

DEFINITIONS

To aid in understanding and administering this policy, the following definitions apply:

Illegal Drugs: drugs which are not legally obtainable and drugs which are legally obtainable but have been obtained illegally.

Controlled Substances: chemical substances and drugs controlled under the laws of the United States of America or by appropriate state law.

Company Property: used in its broadest sense, including all property, facilities, land, parking area, offices, buildings, structures, installations, equipment, vehicles, and any other facilities whether owned, rented, or leased for company use.

Detectable Levels: the measurable presence of an illegal or prohibited drug or substance found in body fluids at levels of detection above the lowest detection level established for the analytical method used in the testing laboratory.

Reasonable Suspicion: a belief based on reasonable, observable, objective, or articulable facts sufficient to lead a prudent supervisor to suspect that the person has been using a prohibited drug, substance, or alcohol.

GROUNDWATER SERVICES, INC.

Under the Influence: being unable to perform work in a safe and productive manner, being in a physical or mental condition which creates a risk to the safety and well-being of the individual, other employees, the public, or to property. Having laboratory evidence of the presence of drugs, alcohol, prohibited or controlled substances, in excess of an identifiable trace quantity in the body.

Possession: actual or constructive care, custody, control, or immediate access.

Drug Paraphernalia: including, but not limited to:

1. Blenders, bowls, containers, spoons, mixing devices used for or intended for use in compounding controlled substances.

2. Capsules, balloons, envelopes and other containers used for or intended for use in concealing or packaging small quantities of controlled substances.

3. Hypodermic syringes, needles, or other objects designed or intended for injecting controlled substances into the human body.

4. Objects used or intended or designed for use in ingesting, inhaling, or otherwise introducing marijuana, hashish, cocaine, or hashish oil into the human body, such as: pipes; water pipes; carburation tubes and devices; smoking and carburation masks; roach clips and other objects used to hold smoking materials; chamber pipes; electrical pipes; air-driver pipes; bongs; ice pipes; and rolling paper not associated specifically with tobacco products.

Metabolite: substance produced by the human body which indicates the presence of an ingested substance.

Nanogram: a normally recognized measure of a metabolite equivalent to .000000001 gram. The unit of 1 nanogram/liter (ng/l) is roughly equivalent to 1 part per billion (ppb).

Immunoassay: a laboratory testing technique to detect trace amounts of a substance in a sample.

Drugs: those to be tested as listed below:

Amphetamines: include three closely related drugs, amphetamine, dextroamphetamine, and methamphetamine. Their street names include: “speed, white crosses, uppers, dexies, bennies, and crystal”. In pure form, they are yellowish crystals that are manufactured in tablet or capsule form. Abusers also sniff the crystals or make a solution to be injected.

Prescription medications used for treatment of sleep disorders and for weight control contain benzedrine and dexedrine. Over-the-counter cold medications contain Ephedrine, Pseudoephedrine, or phenylpropanolamine which, if taken in sufficient quantity, can result in positive test results.

GROUNDWATER SERVICES, INC.

Cocaine: is a drug extracted from the leaves of the coca plant which grows in South America. Like the amphetamines, it is a central nervous system stimulant. Cocaine appears in several different forms. Cocaine hydrochloride is the most available form of the drug and is used medically as a local anesthetic. It is usually a fine, white, crystal-like powder, although at times it comes in larger pieces which on the street are called "rocks". Cocaine is usually sniffed or snorted into the nose, although some users inject it or smoke a form of the drug called freebase.

Marijuana: (grass, pot, weed) is the common name for a crude drug made from the plant Cannabis sativa. The main mind-altering (psychoactive) ingredient in marijuana is THC (delta-9-tetrahydrocannobinol), but more than 400 other chemicals also are in the plant. A marijuana "joint" (cigarette) is made from the dried particles of the plant. The amount of THC in the marijuana determines how strong the effects will be.

Opiates: include opium and opium derivatives such as morphine, codeine, and heroine. Methadone is a synthetic opiate with morphine-like properties. Heroin is the main narcotic in this group which is abused. Prescription drugs may also be abused and include paregoric, which contains opium; cough syrups, Percodan, and Tylenol-3, which contain codeine; methadone, meperidine, and morphine.

Phencyclidine: (PCP) is most often called "angel dust". It was first developed as an anesthetic in the 1950's. However, it was taken off the market for human use because it sometimes caused hallucinations. PCP is available in a number of forms. It can be in a pure, white, crystal-like form.

SEVERABILITY OF POLICY PROVISIONS

If any part of this policy is held invalid by a competent authority, such part shall be invalid; however, the remainder shall continue in full force and effect.

GROUNDWATER
SERVICES, INC.

APPENDIX B

MOTOR VEHICLE SAFETY AND DEFENSIVE DRIVING PROGRAM

GSI Health and Safety Plan

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

GROUNDWATER SERVICES, INC.

APPENDIX B

MOTOR VEHICLE SAFETY AND DEFENSIVE DRIVING PROGRAM

Groundwater Services, Inc. (GSI), is committed to employee safety and the promotion of safe defensive driving practices. Accordingly, GSI has developed a proactive motor vehicle safety and defensive driving program to promote safe driving by all GSI employees. The policy is effective as of October 1, 1991. The tenets of this policy are summarized below.

- **Pre-Employment Screening:** Prior to hiring any employee who will be required to operate a motor vehicle as part of their employment, GSI will obtain and review the most recent available driver record service report for the prospective employee. Employee driving records will be evaluated as part of all hiring decisions for employees required to operate a motor vehicle as part of their employment. In addition, prospective employees with three or greater moving violations within the preceding one-year period will not be eligible for employment with GSI.

- **Monitoring of Employee Driving Practice:** Every twelve months, GSI will obtain the most recent available driver record service report for all GSI employees who are required to operate a motor vehicle as part of their employment. These driving records will be reviewed by the safety program administrator and kept on file at GSI. Based upon the review of the driving safety records, employees may be placed on probation and/or required to attend defensive driving instruction, as discussed below.

- **Defensive Driving Instruction:** All new GSI employees who are required to operate a motor vehicle as part of their employment and

  a) are 25 years of age or younger, or

  b) have at least one moving violation within the preceding one year period

  will be required to attend a Level 1 Driving Safety Awareness Course within one month of beginning employment at GSI. GSI will reimburse the employee for the **first** Level 1 Driving Course, with the employee being responsible for any subsequent courses. Those employees with two or three moving violations within the preceding year will also be required to attend a Level 2 Driving Safety Awareness Course within six weeks of beginning employment at GSI. The Level 1 course is composed of eight hours of classroom instruction, and the Level 2 course is composed of eight hours of classroom instruction and four hours of personalized driving instruction.

  During their employment with GSI, any employee who is required to operate a motor vehicle as part of their employment and who accumulates two moving violations (in company or private vehicles) during a one-year period will be required to attend a Level 1 Driving Safety Awareness Course. Those employees who accumulate three moving violations within a one-year period (in company or private vehicles) will also be required to attend a Level 2 Driving Safety Awareness Course and will be placed on probation. The driving probation program is discussed in more detail below.

GROUNDWATER SERVICES, INC.

- **Employee Probation/Termination:** Any GSI employee who accumulates three or more moving violations within a one-year period will be placed on motor vehicle probation. The terms of probation are as follows:

  a) Accumulation of a fourth moving violation within a one-year period will result in the employee being barred from operating GSI vehicles. If the fourth moving violation is received while operating a company vehicle, the violation will be considered sufficient grounds for immediate termination, at the discretion of the company.

  b) The employee will be required to attend the Level 2 Driving Safety Awareness Course. If the employee has already taken the Level 2 course, they will be required to repeat the course.

  The period of employee motor vehicle probation ends when sufficient time has elapsed such that the employee has two or fewer moving violations within the preceding one-year period.

- **Alcohol and Drug Abuse Prevention:** All GSI employees are required to comply with the terms of the GSI Policy Regarding Drugs, Alcohol, and Other Prohibited Items (see Attachment A). A Driving While Intoxicated (DWI) conviction of any company employee while operating a company vehicle will result in the immediate termination of the employee.

- **Employee Safety Meetings:** Safe driving practice will be discussed as a part of regular GSI safety meetings.

- **Employee Notification:** Copies of the GSI Motor Vehicle Safety Program are distributed to all employees upon hiring as part of the corporate Health and Safety Plan, or upon substantial revision of the plan. A copy of the policy will be posted in the GSI office.

- **Program Administration:** Administrator of the motor vehicle safety program is the corporate safety administrator Robert Lee.

GROUNDWATER
SERVICES, INC.

APPENDIX C

HAZARD COMMUNICATION PROGRAM

29 CFR §1910.1200

GSI Health and Safety Plan

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

GROUNDWATER SERVICES, INC.

APPENDIX C

GROUNDWATER SERVICES, INC.
HAZARD COMMUNICATION PROGRAM

1.0 INTRODUCTION: PURPOSE AND SCOPE OF GSI HAZCOM PROGRAM

The Groundwater Services, Inc., (GSI) Hazard Communication program has been developed to provide the information necessary to enable employees to perform their jobs in a manner which minimizes the potential for illness or injury due to exposure to hazardous chemicals. The program is designed to comply with the Occupational Safety and Health Administration (OSHA) Hazard Communication Standard (also known as "Employee Right to Know") as specified in 29 CFR §1910.1200. This program applies to all chemical usage in the work place, including the GSI office and warehouse as well as job sites.

This program applies to all GSI employees, and it is the responsibility of each employee to follow the procedures and practices outlined in this plan. In addition, employees who oversee the work of subcontractors at GSI job sites must ensure that subcontract personnel comply with applicable portions of the plan as specified below.

While GSI is not directly involved in chemical manufacturing, importation, or transportation, GSI employees routinely perform work at chemical manufacturing facilities and other sites where a general knowledge of potential chemical hazards is essential. In addition, many projects require the use of chemicals, some of which are hazardous, for tasks such as well development and treatment, field testing of soil and groundwater samples, and other miscellaneous support functions.

The primary potential for chemical exposure for GSI employees is in conjunction with the investigation and remediation of hazardous waste sites. Although hazardous wastes regulated under the Resource Conservation and Recovery Act (RCRA) are explicitly excluded from the application of the Hazcom Standard, the GSI Hazard Communication Program also describes procedures for communication of potential chemical hazards associated with hazardous waste sites.

While home usage of chemicals is not regulated under the Hazcom standard, GSI encourages employees to apply the knowledge they gain in the workplace to the home environment. Family members should be instructed in the safe use and handling of household chemicals, and appropriate precautions should be taken to prevent harmful chemical exposure in the home.

The company Safety Administrator is responsible for preparation, implementation, and any needed revision of the GSI Hazard Communication Program. Employees with questions regarding this program should contact the Safety Administrator

GROUNDWATER SERVICES, INC.

2.0 MATERIAL SAFETY DATA SHEETS (MSDS)

General Information: A Material Safety Data Sheet (MSDS), is required for each hazardous chemical used in the work place. As discussed in Section 4.0, MSDSs for chemicals encountered in soil and groundwater at hazardous waste sites are also required for preparation of site-specific health and safety plans. The MSDS contains important information on the potential hazards of exposure to the chemical, means of preventing harmful exposure, and appropriate response measures in the event of release or exposure. All employees working with any chemicals, whether in the field, warehouse, or office, should know how to use an MSDS, and should be familiar with the hazards of the particular chemicals with which they work. As specified in 29 CFR §1910.1200(g) the MSDS must contain, at a minimum, the following information:

- the identity of the chemical and any hazardous ingredients;
- physical and chemical characteristics and physical hazards of the chemical;
- health hazards, including whether the chemical is carcinogenic;
- primary routes of entry to the body;
- applicable exposure limits (e.g., PEL, TLV, IDLH, etc.);
- precautions for safe handling and use, and control measures (e.g., personal protective equipment (PPE));
- emergency and first aid procedures; and
- the name, address, and phone number of the preparer of the MSDS and the date of preparation.

Acquisition of MSDSs: When chemicals such as testing reagents, instrument calibration standards, well treatment chemicals, cleaning agents, lubricants, etc., are procured for use in the work place, including the GSI office, warehouse, and/or job site locations, an MSDS must be obtained. The person ordering or purchasing the chemical is responsible for supplying an MSDS to the CSO. Most chemical suppliers routinely provide an MSDS when chemicals are delivered or picked up. However, the individual placing the order must verify that an MSDS will be provided with the chemical. Since the MSDS is frequently sent directly from the supplier to the CSO without explanation, GSI employees who order chemicals for a particular use should, upon ordering, inform the CSO of what chemical has been ordered and from whom, the approximate quantity, and its intended use. A form for this purpose is attached to this plan; additional copies are available from the CSO.

An MSDS must also be obtained for any chemical purchased at hardware or building supply stores or other retail establishments. If the establishment can not provide a copy of the MSDS, the individual making the purchase should contact the manufacturer directly, and have them provide a copy of the MSDS immediately. The MSDS should be consulted prior to use of the chemical. (Note that the manufacturer will frequently include a telephone contact number and/or hazard data on the container label). It is not necessary to obtain an MSDS with every purchase, as long as an MSDS is already on file at GSI.

Location and Distribution of MSDSs: MSDSs for chemicals used in the work place are kept in clearly labeled black and yellow loose-leaf notebooks at two locations: 1) at the GSI office, in the office of the CSO, and 2) at the GSI warehouse in the front office

GROUNDWATER SERVICES, INC.

room. Neither book may be removed from its location, except by special permission of the CSO. The files are arranged alphabetically by the common name of the chemical. When an MSDS is received, it must be routed to the CSO, who will place a copy of the MSDS in the office file and provide a copy for the warehouse file. The warehouse MSDS file is maintained by Ben Medina. Superseded versions of MSDSs must be removed from the books and replaced with the current versions.

At the front of each notebook is a listing of chemicals used by GSI. The list identifies all chemicals currently in use or storage at the GSI office or warehouse, as well as chemicals which have been used in the past and which may be periodically present at either the office or warehouse, or on job sites. The chemical inventory is updated by the CSO upon procurement of additional chemicals. The listing of chemicals is also included in this document as Table 1. Updates to Table 1 of the Hazcom program will be distributed to all employees annually or more frequently, if needed.

On tasks which require the use of hazardous chemicals in the field, such as well development and treatment, field testing of soil and groundwater, equipment decontamination, and the like, the project manager or project safety officer should review the MSDS for the chemical(s) to be used and brief project personnel on their hazards and proper handling and use. A copy of the MSDS should be attached to the project health and safety plan, copies of which must be placed in the job file and carried into the field.

Some GSI clients also require that an MSDS for any material brought on-site be provided to their safety representative. This includes materials brought on-site by our subcontractors. Compliance with this requirement is the responsibility of the project manager.

3.0 CONTAINER LABELING

All hazardous substances received at the work place should be labeled by the manufacturer/distributor with the identity of the chemical and appropriate hazard warnings. These labels must not be removed from the container, or defaced. If the contents are to be placed in other containers for storage or use, (e.g., if a relatively large quantity of the material is to be placed in several smaller containers for use in the field) the additional containers must all be labeled with the product name and all appropriate hazard warnings.

Portable containers into which hazardous chemicals are transferred from labeled containers do not require labels *only if* they are intended for the immediate use of the employee who performs the transfer. If the chemical is to be stored after the "immediate use" or the container is to be passed on to other employees for their use, the container must be labeled.

4.0 CHEMICALS ENCOUNTERED DURING OPERATIONS AT HAZARDOUS WASTE SITES

As stated in 29 CFR 1910.1200 (b)(6), the Hazcom Standard

> *"does not apply to : (i) Any hazardous waste as such term is defined by the Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act of 1976 as amended (42 U.S.C. 6901 et seq.), when subject to regulations issued under that Act by the Environmental Protection Agency."*

However, because hazardous substances encountered in soil and groundwater at hazardous waste sites represent the primary mechanism for potential chemical exposure for GSI employees, this section provides general guidelines for hazard communication applicable to such sites. Additional information is provided in the *GSI Health and Safety Program*.

As described in the *GSI Health and Safety Program*, a site-specific health and safety plans is required on most field projects. The site-specific plan must include information on any known or likely chemical hazards present at the site, and procedures for mitigation of those hazards, (e.g., monitoring, PPE, etc.). The primary source of this information is the MSDS. MSDSs for chemicals of concern at the site should be attached to the site-specific plan and *must be present at the job site* whenever work involving potential for chemical exposure is being performed.

For chemicals encountered in soil and groundwater at hazardous waste sites, an MSDS can frequently be obtained through the facility owner. In addition, MSDSs may be obtained via the internet. When preparing a site-specific health and safety plan, current sources of exposure limit values, such as the annual publication by the ACGIH, *Threshold Limit Values for Chemical Substances and Physical Agents*, or the *Respirator Selection Guide,* published annually by the 3M Company, should be consulted. These can be found in the office of the Safety Administrator.

5.0 EMPLOYEE HAZCOM INFORMATION AND TRAINING

A copy of the *GSI Hazard Communication Program* shall be provided to all new employees and an orientation to the program conducted as part of the new-employee orientation. Copies of any revisions to the Hazcom Program, including updates of the chemical inventory shall be provided to all employees upon approval by the CSO. Copies of the plan shall also be kept in the MSDS file notebooks at the GSI office and warehouse. The original is on file in the office of the CSO.

Hazcom refresher training is provided for all field workers, field supervisors, and project managers annually and is mandatory. This training is generally conducted by the GSI CSO in conjunction with the annual Hazwoper refresher class under 29 CFR 1910.120. Hazcom training will include, at a minimum, the following subjects:

- a detailed review of the GSI Hazcom program

GROUNDWATER SERVICES, INC.

- use of the MSDS, including GSI procedures for distribution, etc.
- hazardous chemical properties and chemical hazard recognition
- detection and monitoring methods
- protective measures, such as engineering controls, work practices, and PPE.

Special sessions will be held more frequently for affected employees, as needed, whenever a new chemical hazard is introduced into their work place.

GROUNDWATER
SERVICES, INC.

APPENDIX D

SAFETY PROCEDURE FOR ELECTRICAL/HAZARDOUS ENERGY LOCKOUT

29 CFR §1910.147

GSI Health and Safety Plan

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

GROUNDWATER SERVICES, INC.

APPENDIX D

SAFETY PROCEDURE FOR ELECTRICAL/HAZARDOUS ENERGY LOCKOUT

Groundwater Services, Inc., Houston, Texas.

1.0 PURPOSE AND SCOPE

1.1 Purpose

This procedure is established to comply with OSHA Regulations (29 CFR §1910.147) concerning control of hazardous energy. The procedure establishes the minimum requirements for the lockout or tag-out of energy isolating devices during maintenance and repair operations. It shall be used to ensure that machines and electrical equipment are isolated from all sources of potentially hazardous energy, and are locked out or tagged out before employees perform service or maintenance activities where the unexpected energizing, startup, or release of stored energy could cause injury.

1.2 Scope

This procedure applies to all employees of Groundwater Services, Inc. (GSI) and their subcontractors involved in the installation, service, and maintenance of powered machinery and equipment. Such equipment currently in use by GSI is limited to electric-powered sump pumps, submersible groundwater pumps, and associated motor control equipment.

Accordingly, this procedure is limited to the lock out of electrical equipment and does not cover the installation or removal of "Blinds," lockout of hydraulic-powered or pneumatic-powered equipment, or lock out of radioactive energy sources. GSI employees and subcontractors are specifically instructed not to enter any vessel or activate any valves or other devices relating to hydraulic, pneumatic, radioactive, or process chemical systems under any circumstance. Should GSI's scope of services be expanded in the future such that access to these types of systems becomes necessary, this procedure will be revised and expanded as appropriate to comply with OSHA standards before such work is performed.

3.0 DEFINITIONS

"Affected employee"

An employee whose job requires him/her to operate or use a machine or electrical equipment on which servicing or maintenance is being performed under lockout or tag-out, or whose job requires him/her to work in an area in which servicing is being performed.

<u>"Authorized employee"</u>

A person who implements a lockout/tag-out system procedure on machines or equipment to perform maintenance or service on that machine or equipment.

<u>"Capable of being locked out"</u>

An energy isolating device is considered capable of being locked out if it is designed with a hasp or other attachment or integral part to which, or through which a lock can be affixed, or if it has a locking mechanism built into it.

<u>Energized</u>

Connected to an energy source or containing residual or stored energy.

<u>"Energy isolating device"</u>

A mechanical device that physically prevents the transmission or release of energy, including, but not limited to the following: a manually operated electrical circuit breaker, a disconnect switch, or a manually operated switch by which the conductors of a circuit can be disconnected from all ungrounded supply conductors.

<u>"Lockout"</u>

Placement of a lockout device on an energy isolation device ensuring that the energy isolating device and the equipment being controlled can not be operated until the lockout device is removed.

<u>"Lockout Device"</u>

A device that utilizes a positive means, such as a keyed lock, to hold an energy isolating device in the safe position and prevent the energizing of a machine or equipment. For the purpose of this procedure, a keyed padlock, color-coded OSHA yellow, identified as a lockout device, and labeled with the name of the owning authorized employee will be used.

<u>"Machinery or Equipment"</u>

As used in this procedure, machinery or equipment refers to any mechanical or electrical device containing or utilizing potentially hazardous energy, including pumps, motors, etc.

<u>"Tie Wrap"</u>

A non-reusable self-locking device, such as a one-piece nylon cable tie, which is attachable by hand and non-releasable with a minimum unlocking strength of 50 pounds.

"Tag-out"

The use of lockout tags and tie wraps on energy sources which can not be locked out. A tag-out is not as secure as a lockout and may only be used when a lockout is not feasible.

3.0 RESPONSIBILITIES:

3.1 GSI Responsibilities

GSI is responsible for preparation of a lockout procedure in conformance with the 29 CFR § 1910.147, including proper training of its authorized and affected employees in that procedure, and for providing an adequate supply of locks and other necessary lockout devices.

3.2 Authorized Employee Responsibilities

The authorized employee is responsible for safe and proper implementation of this lockout procedure (i.e., for preventing accidental operation or energizing of machinery or equipment by proper use of lockout devices).

3.3 Individual/Affected Employee Responsibilities

Persons performing inspection or repair work are responsible for their own safety and protection by having satisfied themselves that the authorized employee has correctly locked out the equipment to be repaired. The authorized employee will assist the individual in reviewing the lockout plan, verifying the lockout, and testing start switches after lockout. It is mandatory that the maintenance and or operations person try the start switch or switches to verify that the proper equipment has been locked out and that there are no additional energy sources.

4.0 POLICY AND PROCEDURES

4.1 Lockout/Tag-out Procedure

Prior to any maintenance or service to be performed on equipment covered by this procedure (i.e., electric sump pumps, submersible groundwater pumps, and associated motor control equipment), the authorized employee will notify all affected employees of the lockout. The equipment will then be shut down and locked out by the authorized employee.

The lock may be placed on the main power switch located outside the circuit breaker box, on the circuit breaker box itself after the applicable breaker switch has been switched to the off position, or on the switched-off circuit breaker switch using a specifically designed breaker switch lock out device.

Each lockout device will have a proper lockout tag stating the reason for the lockout, the name of the authorized employee performing the lockout, he date of the lockout and, if the

GROUNDWATER SERVICES, INC.

equipment is to be out of service beyond that date, the expected time period of the lockout. A sample tag is attached.

Acceptable lockout devices include color-coded keyed padlocks with a label identifying it as a lockout device and bearing the name of the authorized employee. Other devices such as multi-holed hasps (if two or more employees are to work on the locked out equipment) and circuit breaker lockouts may be used in conjunction with the padlocks. Each authorized employee will be issued an adequate number of keyed locks and will retain sole possession of the keys, except for spares in the possession of the GSI company safety officer. All lockout equipment will be substantial enough to prevent removal without the use of excessive force or unusual techniques such as bolt cutters or other metal cutting tools. In cases where placement of a lock is not possible, a tag-out label on a tie wrap may be substituted.

4.2 Verification of Deactivation/De-energizing

Once all sources of energy have been locked/tagged out, the authorized employee verify that the equipment has been de-energized by an appropriate method. For equipment on which a switch is located down-line of the lockout point, the switch will be tried prior to proceeding with the work. A volt meter will be used to verify the absence of potentially hazardous energy from electrical connections prior to disconnection.

4.3 Equipment Startup

At the completion of the job, the authorized employee is responsible for verification that the job is complete and the need for the lockout is over. At this point, the job site will be inspected to verify that restart of the equipment will not endanger personnel. All lockout devices will be removed by the authorized employee(s). The equipment may then be restarted.

4.4 Application of General Procedure

Electrical equipment currently in use by GSI is limited to pumps and related motor control equipment powered by 110 or 220 volt current. The scope of services provided by GSI does not involve maintenance or repairs to systems utilizing chemical, thermal, pneumatic, hydraulic, or radioactive energy. In addition, equipment operated by GSI meet the following criteria, specified in 29 CFR § 1910.147 (c)(4), permitting application of a single general lockout procedure and providing an exemption from development of a specific procedure for each piece of equipment:

1) The machine or equipment has no potential for residual or stored energy or reaccumulation of stored potentially hazardous energy after shut down;

2) The machine or equipment has a single energy source which can readily be identified and isolated;

3) The isolation and locking out of that energy source will completely deenergize and deactivate the machine or equipment;

4) The machine or equipment is isolated from that energy source and locked out during servicing or maintenance;

5) A single lockout device will achieve a lockout condition;

6) The lockout device is under the exclusive control of the authorized employee performing the servicing or maintenance;

7) The servicing or maintenance does not create other hazards for other employees;

8) GSI, in utilizing this exception, has had no accidents involving the unexpected activation or re-energizing of the machine or equipment during servicing or maintenance.

Accordingly, the lockout procedure described above will be followed for maintenance and service of all pumps and related equipment.

4.5 Inadvertent/Abandoned Locks

In the event that a lockout is inadvertently left on equipment or is abandoned, the lock may be removed by the GSI company safety officer or his designee. An attempt will be made to immediately notify the individual of the lock removal, and a written record made of the removal, including the location of the lockout, the individual who performed the lockout, and the individual(s) authorizing and performing the removal. The record will be maintained by the GSI company safety officer.

4.6 Training

All affected and authorized employees will be thoroughly trained in this procedure, and refresher training will be conducted annually at a minimum. Any GSI subcontractors performing work for GSI under a lockout will also be trained in the procedure, as needed. Additional training will be performed as necessary (e.g., in the event of deficiencies in implementation). Records of training will be maintained by the GSI company safety officer.

4.7 Verification of Compliance

The lockout procedure will be reviewed annually, at a minimum, to verify that the procedure is being followed and to assess the need for revision of the procedure. In addition, inspections will be conducted annually to ensure the procedure is being properly implemented.

4.8 Lockout Procedure Violations

As required by OSHA, any person violating lockout procedures will be disciplined. First violation of the lockout procedure will result in a warning and mandatory review of the lockout procedure. Repeated violation of the procedure will result in further disciplinary action, including possible dismissal.

GROUNDWATER SERVICES, INC.

APPENDIX E

Forms for
Site-Specific Health and Safety Plan
Daily Site Safety Record
Tailgate Safety Meeting

29 CFR §1910.1200

GSI Health and Safety Plan

Groundwater Services, Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098
(713) 522-6300

GROUNDWATER
SERVICES, INC.

GROUNDWATER SERVICES, INC.

PROJECT HEALTH AND SAFETY PLAN for

____
Project Name

____
Project Location

GSI Job No.		Revision No.:	
Plan Prepared By:		Date:	
Plan Reviewed By:		Date:	

Plan Approved: ______________________ Date: ______________

ACKNOWLEDGEMENT

I, the undersigned, have been provided with a copy of this Site-Specific Project Health and Safety Plan. I have read the Plan, have attended a project safety orientation session conducted by Groundwater Services, Inc. (GSI), and have had the opportunity to ask questions about health and safety issues relating to this project. I understand that it is my responsibility to abide by this Plan, and that physical injury, damage and other harm to myself or others could result from my failure to do so.

Name & Company(please print)	Social Security No.	Signature	Date

GROUNDWATER SERVICES, INC.

PROJECT HEALTH AND SAFETY PLAN

1.0 SCOPE AND APPLICATION

This Project Health and Safety Plan has been prepared in accordance with 29 CFR §1910.120, and is a site-specific supplement to the GSI company Health and Safety Plan (GSI HASP), which specifies GSI's general health and safety policies and procedures. This site-specific plan is to be provided to all site workers under the direction of GSI for their review. In addition, this plan, the GSI HASP, and applicable client safety guidelines will remain on-site at all times during the project, and will be available to all project personnel upon request from the GSI Site Safety Officer (SSO) or other designated representative.

This plan specifies health and safety protocol to be followed during implementation of the project work scope by all site personnel under the direction of GSI, including employees and subcontractors. In the event of conflicting standards between this plan or the GSI HASP and client health and safety requirements, the more protective standard shall apply. All personnel are required to comply with this plan and to indicate their agreement to do so by signing the cover page.

2.0 PROJECT DESCRIPTION

2.1 General Information

Client/Site Owner	
Project Name and General Description	
Project Location (Physical Address)	
Detailed Location Information	
Start Date/Duration/ Other Schedule Info.	

2.2 Site Description: Provide site description / attach site plan

Information should include 1) General description: (e.g., chemical manufacturing facility, tank farm, land fill, surface impoundment, commercial/retail development, undeveloped); 2) Approximate size; 3) Topography/terrain/surrounding land-use: (e.g., flat, gently or steeply sloping; ground surface paved, unpaved, graveled, vegetated, wooded surface water bodies; located in industrial, residential, commercial or undeveloped area; 4) Major features of developed areas: manufacturing facilities, tank farms, warehouses, etc.

GROUNDWATER SERVICES, INC.

2.3 Project Tasks: Outline major tasks, attach detailed workplan and/or operating procedures

Describe tasks and methods in sufficient detail to facilitate analysis of potential hazards.

EXAMPLE:

Collect surface soil samples from depths up to XX ft bgs using hand augers
Drill & install monitoring wells using hollow-stem augers to depths up to YY ft bgs in within battery limits of process areas.
Collect potentially contaminated soil samples, conduct field screening using OVA
Decontaminate drilling equipment using hot-water pressure wash
Construct concrete surface pad completions
Develop wells by surging and pumping using gasoline powered pumps or electrical pumps powered by gasoline-fired generator
Collect groundwater samples using electrical pump or bailers
Collect soil cuttings and purge water in drums and move to designated storage area by fork-lift
Etc.

GROUNDWATER SERVICES, INC.

3.0 EMERGENCY RESPONSE PROCEDURES

Specify emergency reporting contact. Provide Plant Emergency Response Contact with phone number(s) where applicable. Call 911 for emergencies located elsewhere.

Emergency related to underground utilities in Texas are reported to 1-800-DIG-TESS

Describe plant siren/ alarm signals, if applicable, and response

Location of emergency assembly area(s)

Describe other applicable emergency response measures to be taken

Location and phone number of nearest hospital with emergency room (attach map)

GROUNDWATER SERVICES, INC.

4.0 PROJECT ORGANIZATION, PERSONNEL, & TRAINING REQUIREMENTS

4.1 Key Personnel

Position	Name	Phone (Pager/Cell Phone)
GSI Project Team Leader (PTL)		713-522-6300
GSI Site Manager		
GSI Site-Safety Officer (SSO)		
Client Project Manager		
Client H&S Representative		
Subcontractor Foreman		

4.2 Training Requirements – Check all that apply and list any additional

	OSHA 40-hr HAZWOPER		
	Contractor Safety Council (CSC) -Basic +		
	Site-Specific (CSC or on-site)		
	Unit specific		

4.3 Requirements for Respirator Use

Will respirator use potentially be required? ______Yes ______No

If yes, GSI Respiratory Protection Plan, found in Section 6.0 of the GSI HASP, is applicable. Affected personnel must have physician's written opinion certifying fitness to use respirator based on pulmonary function test and other considerations, be trained in proper respirator use, and have quantitative fit test.

4.4 Personnel Documents

List documentation of training or medical fitness project personnel will be required to provide.

5.0 POTENTIAL HAZARDS & HAZARD CONTROL MEASURES

5.1 General Site Access Control

Specify site control measures as necessary to prevent unauthorized persons from entering work area (e.g., fencing, barricades, tape, signs, etc.)

5.2 Project Personnel Access Control

Specify sign-in and sign out procedures for project personnel, and means of notifying site manager if unable to be on-site.

GROUNDWATER SERVICES, INC.

5.3 Underground Utilities Clearance

Specify procedures for obtaining clearance of locations for drilling, excavation, or other subsurface penetrations. If using Texas Excavation Safety System (TESS) 2-working days notice prior to start-up is required. Phone 1-800-DIG-TESS or Fax 1-800-690-1291. Specify date of call, response and case or serial no. For clearance of site-owned utilities, provide contact and response information.

5.4 General Work Hazards and Avoidance

General work hazards include slip, trip, and fall hazards, head or foot injuries from falling or dropped objects, strains from over-exertion or incorrect lifting, electrical shocks, etc. These hazards can be controlled by good housekeeping measures and safe work practices, as outlined below. See also GSI HASP.

Housekeeping Measures:

- Excess brush or high vegetation should be cleared from the work area to the extent practical prior to start of the job.
- The job site must be kept clean and free of trash and debris. Trash will be placed in bags or other suitable containers when generated. Disposable PPE must be disposed in designated containers upon removal.
- Materials such as lumber, well screen and riser pipe, filter pack sand, cement, etc. will be neatly stored in a designated area.
- Tools and equipment must be returned to the tool box or designated area when no longer in use.

General Safe Work Practices:

- Use buddy system. Use
- Stay alert at all time to activities in your surroundings. Watch for on-coming vehicles, other workers, and overhead hazards.
- Work at a deliberate pace; do not rush a job.
- Avoid heavy lifting and lift with knees bent.
- Use tools only for their intended use, and make sure tools are in good condition. Inspect power tool and extension cords prior to use.
- Maintain safe distance between drillrig mast or other overhead equipment and overhead lines.
- Avoid unauthorized entry to restricted areas including confined space areas.
- Do not operate plant process equipment; do not open or close valves
- Proper PPE (specified below) must be worn at all times. PPE must be inspected regularly and properly maintained.
- Remove gloves and wash hands before handling food or tobacco products.

5.4 Fire and Explosion Hazard Mitigation

- All drilling or excavation locations must be properly cleared for the presence of underground utilities prior to drilling or digging. (Utility clearance procedures are specified above).

GROUNDWATER SERVICES, INC.

- Gasoline and other fuels must be stored in steel safety cans with mesh flame arresters and spring-mounted relief vent mechanisms. Flammable and combustible materials including paints and solvents must be properly stored away from sources of ignition.
- Fire extinguishers must be present on all vehicles and drilling and excavation equipment, and in all areas where spark producing equipment is in use.

Other Measures (check as applicable)
____ Smoking permitted only in designated areas, or
____ Smoking permitted only in designated areas
____ Matches and lighters not permitted onsite
____ Hot-work permits must be obtained for spark-producing equipment in designated areas.
____ Other ____

5.5 Heat-Related Disorders

The major varieties of heat-related disorders, their related symptoms and appropriate treatment are listed below in order of increasing severity.

Condition & Related Symptoms	**Heat Stress**	**Heat Exhaustion or Heat Syncope**	**Heat Stroke**
Cramping	May be present	May be present	Absent
Mental State	Faint, dizzy, fatigue	May be disoriented	Stupor or coma
Skin & Complexion	Cool, moist, flush; rash may be present.	Cool, pale, moist	Red, hot, dry
Temperature	Normal	Normal to low	Very high (>105° F)
Pulse	Rapid (>110 beat /min)	Rapid, weak	Rapid, bounding
Blood Pressure	May be low	May be low	May be high in early stages
Treatment	Give water & electrolytes, loosen or remove clothing, move to shade	Give water & electrolytes, loosen or remove clothing, move to shade	Provide rapid cooling by immersion; cover in wet cloth and transport to emergency room

Prevention Measures: All heat disorders are caused by loss of fluids and the body's inability to cool itself. Heat stress can be prevented by the following measures:

- Pre-hydrate before going into the field: water or water-electrolyte drinks are preferable to caffeinated beverages or soft drinks. Refrain from alcohol the night before field work.
- In the field drink frequently. Numerous small drinks at a tepid temperature are better than rapid, large volume intakes of iced drinks.
- Rest at least a few minutes every hour or two.
- Observe co-workers for signs of heat stress.

5.6 Heavy Equipment Operations

Drilling and other equipment must be in good condition. Particular attention should be paid to the condition of cables and hoisting equipment. The equipment must be equipped with a back-up beeper. Barricades or caution tape should be used as needed to exclude unauthorized personnel from the work area.

During drilling, the drillrig should be positioned to allow for adequate work room and the area kept free of trip and slip hazards. Care must be taken to avoid the catching of loose clothing in moving parts, and to keep hands free of pinch points. Proper PPE including hard hat, safety glasses, gloves, hearing protection, and safety shoes must be worn.

5.7 Confined Space and Excavation Safety

All personnel must obey all posted restrictions on entry to confined spaces. Excavations deeper than 4 ft should not be entered for any purpose unless 1) the excavation walls are properly shored or are sloped at a 1:1 slope, or less steep, and there is no danger of collapse or engulfment; 2) a suitable means of egress such as ramp, stairs or ladder is located so as to require no more than 25 ft of lateral travel to reach it; and 3) testing demonstrates a hazardous atmosphere is not present.

5.8 Potential Chemical Exposure Hazards

Summarize primary constituents of concern, relevant exposure levels, and the maximum expected concentrations in soil and/or groundwater, to the extent known. Provide Material Safety Data Sheets (MSDS) in Attachment A.

CONSTITUENTS OF CONCERN (COCs)	**Exposure Limits[1]**			**Max. Expected Concentration or Free-Phase (FP)**		**Health Hazard Target Organ Route of Entry[2]**
Chemical Name CAS No.	**PEL/ TLV (ppm)**	**STEL (ppm)**	**IDLH (ppm)**	**Soil mg/kg**	**Water mg/L**	Ca = Carcinogen, Abs = skin absorption Con = skin or eye contact Inh = Inhalation. Ing = ingestion

1 Unless otherwise noted, Permissible Exposure Limits (PEL) and Threshold Limit Values (TLVs) are permissible time-weighted average exposure limits (ppm in air) which must not be exceeded for an 8-hour work-day/40-hour work week. Short-Term Exposure Limits (STELs) must not be exceeded over a 15-minute period. IDLH –Immediately Dangerous to Life or Health must no be exceeded at any time. NPV = No published value. ND = Not determined
2 See also NIOSH Pocket Guide to Chemical Hazards.

To minimize potential chemical exposure, the following measures will be taken:

- MSDS must be provided for any chemical brought on-site for project use.
- Workers should remain upwind of contaminated materials to the extent practical.
- PPE specified below will be worn prevent skin or eye contact with constituents.
- Air quality monitoring will be conducted and respiratory protective equipment used as needed, as described below.
- Eating, drinking, smoking, gum chewing and oral tobacco use are not permitted in areas where chemical exposure could occur.

GROUNDWATER SERVICES, INC.

- Workers must remove gloves in the work area and drink from a water source outside the immediate work zone.
- PPE must be removed and hands thoroughly washed prior to breaking for meals.

5.9 Other Potential Hazards

List other potential hazards associated with the site and/or specific tasks and describe hazard mitigation methods.

6.0 AIR QUALITY MONITORING

Air Monitoring Instrument

______ OVA 128 Calibrated to methane standard

______ Drager Tube (specify compound & use)______________________________

______ Personnel Badges (specify compound & use)________________________

______ Lower Explosive Level (LEL) _______________________________________

______ Other (Specify) ____

Monitoring Frequency and Location

Identify tasks during which air monitoring is to be performed?

Specify where will monitoring be performed (e.g., Worker's breathing zone , site perimeter, contaminant source area, or other area) and Monitoring Frequency (e.g., Continuous, Periodic {hourly, etc.}, on detection of noticeable odor)

7.0 PERSONAL PROTECTIVE EQUIPMENT (PPE)

7.1 Level D PPE

A minimum of Level D PPE is required for all site personnel at all times, upgraded as necessary depending on task and conditions. Basic Level D PPE shall include the following elements: **1) Hard Hat** (w/ mono goggles); **2) Safety Glasses** (w/side shields); **3) Safety Shoes** (w/steel toes); **4) Body Covering** (long pants, shirt w/ sleeves, collar). Basic Level D equipment will be supplemented as follows:

GROUNDWATER SERVICES, INC.

SUPPLEMENTAL LEVEL D PPE

	Item	When/Where to be Used
______	Flame Retardant Clothing (FRC)	______
______	Hearing Protection	______
______	Work gloves	______
______	Latex or vinyl surgical gloves	______
______	Neoprene or Nitrile gloves	______
______	Tyvek Coveralls	______
______	Polycoat Tyvek Coveralls	______
______	Chemical-resistant boots	______
______	Face Shield	______
______	______	______
______	______	______

7.2 Level C PPE

Specify action level conditions for Level C PPE (use of Air-Purifying Respirator)

(e.g., Total organic vapors measured in worker breathing zone exceed __ ppm for sustained 1-minute interval)

Specify equipment and limitations

______Half-face Respirator up to ______ ppm, TOV or ___ ppm (compound) by Draeger

______Full Face Respirator up to ______ ppm, TOV or ___ ppm (compound) by Draeger

Specify Cartridge Type____________________________________

Specify action level conditions for Level B (Supplied Air) if applicable, or suspension of work.

7.3 Level B PPE

Specify Level B Equipment (pressure demand, continuous flow, etc.).

Specify Level B Procedures (personnel, air supply monitoring, etc.).

Specify conditions For Project Shut-down.

GROUNDWATER SERVICES, INC.

8.0 DECONTAMINATION PROTOCOL

Specify procedures for personnel decontamination and management of disposable PPE.

Specify procedures for response to non-emergency chemical release.

9.0 ADDITIONAL INFORMATION

Provide any additional information, procedures, or instructions as needed.

GROUNDWATER
SERVICES, INC.

SITE SAFETY MEETING

Project/Location: ______________________________ GSI Job No.__________
____ Page 1 of 1
Site Safety Officer:____________________________ Date: _____________

Meeting Conducted By:__________________
Meeting Attended By:

Name	Company	Signature
1)		
2)		
3)		
4)		
5)		
6)		

______Additional Personnel (See Next Page)

Tasks to be Performed

____

____

Potential Hazards and Hazard Avoidance Measures

Mechanical Hazards: ____

____

Heat stress: ____

____

Chemical exposure: ____

____

Biological hazards: ____

Other: ____

____

GROUNDWATER SERVICES, INC.

DAILY SITE SAFETY RECORD

Project/Location: ______________________________

____

Site Safety Officer:______________________________

GSI Job No.________________

Page 1 of ________________

Date:______________________

Field Personnel

Name	Company	Time Onsite-Offsite	Time Onsite-Offsite
1)			
2)			
3)			
4)			
5)			
6)			

______Additional Personnel (Attach additional sheets as needed.)

Work Item/Personal Protective Equipment Level

Task: ____

Personnel: ______________________________ PPE: ______________________________

Task: ____

Personnel: ______________________________ PPE: ______________________________

Air Quality Monitoring: ______ See Record (next page) Not Required__

Safety Awareness Issues Discussed: ______________________________________

____

____

ACCIDENTS/INJURIES/INCIDENTS

(Description of Incident, Actions Taken. Attach additional sheets as needed)

____

____

GROUNDWATER SERVICES, INC.

DAILY SITE SAFETY RECORD

GSI Job No.________________
Page 2 of ________________
Date ____________________

Air Quality Monitoring:

______Foxboro OVA 128
Calibration Check:
(95 ppm Methane Gas)

______Other (Specify) ________________________
10 X Scale Reading (ppm)_______________
100 X Scale Reading (ppm)_______________

Time	Activity	Sample Point	Reading* (ppm)

* Reading above background, sustained for 1 minute period.

Action Level _ ppm Action Level Exceeded? ________________________

Action Taken____

Remarks____

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix I

Federal and State Vapor Intrusion Resources

APPENDIX I: FEDERAL AND STATE VAPOR INTRUSION RESOURCES

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Federal and State Vapor Intrusion Resources

Federal

U.S. EPA:	www.epa.gov/correctiveaction/eis/vapor.htm
	www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm
	www.epa.gov/ATHENS/learn2model/part-two/onsite/JnE_lite.htm
U.S. EPA Region III:	www.epa.gov/reg3hwmd/risk/index.htm
U.S. EPA Region IX:	www.epa.gov/region09/waste/sfund/prg/index.htm

State

AL:	www.adem.state.al.us/WaterDivision/Ground/UST%20GW/GWUSTCorrAction.htm
AK:	www.dec.state.ak.us/spar/csp/guidance/draft_vap_intr_tm_6_28.doc
CA:	www.dtsc.ca.gov/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=11492
CO:	www.cdphe.state.co.us/hm/indoorair.pdf
	www.oil.cdle.state.co.us
CT:	www.dep.state.ct.us/wtr/regs/RvVolCri.pdf
FL:	www.dep.state.fl.us/waste/categories/wc/pages/cleanup/default.htm
GA:	www.gaepd.org/Documents/index_haz.html
IN:	www.in.gov.idem/programs/land/risc/announcements.html#vapor
KS:	www.kdheks.gov/ber/download/KS_VI_Guidance.pdf
LA:	http://www.deq.louisiana.gov/portal/tabid/1569/Default.aspx
ME:	www.maine.gov/dep/rwm/petroleum/pdf/inhaexpfg.pdf
MA:	www.mass.gov/dep/cleanup/laws/vph_eph.htm
MI:	www.michigan.gov/deq/0,1607,7-135-3311_4109_9846_30022_101581--,00.html#RRD_01
MN:	www.pca.state.mn.us/publications/c-prp4-01a.pdf
NH:	www.des.state.nh.us/desguid.htm
NJ:	www.nj.gov/dep/srp/guidance/vaporintrusion/vig.htm
NY:	www.health.state.ny.us/environmental/investigations/soil_gas/svi_guidance/
NC:	www.enr.state.nc.us/
OH:	www.epa.state.oh.us/derr/rules/vapor.pdf
OK:	www.epa.gov/earth1r6/6pd/rcra_c/pd-n/screen.htm
OR:	www.deq.state.or.us/wmc/tank/rbdm.htm
PA:	www.depweb.state.pa.us/landrecwaste/cwp/view.asp?A=1243&Q=465356
SC:	www.scdhec.gov/eqc/lwm/index.html
TN:	www.state.tn.us/environment/dor/sfdregs.shtml
WA:	www.ecy.wa.gov/biblio/9406.html
WI:	http://dhfs.wisconsin.gov/eh/air/pdf/VI_guide.pdf

December 21, 2007

Environmental Security Technology Certification Program
(ESTCP)

DETAILED FIELD INVESTIGATION OF VAPOR INTRUSION PROCESSES

Appendix J

Response to Reviewers Comments

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

1. The Final Report needs to be prepared as a stand alone document (i.e., all of the project data and interpretation should be included in this report). The current version of the Final Report instead references previous interim reports, etc. The data and interpretation presented in those reports should be provided in this final report.

Response: Agreed.

Revision: The final report has been revised to incorporate the white paper and the data and interpretation from interim reports needed to make the report a stand-alone document.

2. A reliable vapor intrusion investigation approach was listed as one of the performance objectives of the research. This evaluation was provided in a separate white paper (Recommendations for the Investigation of Vapor Intrusion), and is referenced as such in the final report. The white paper results should be incorporated into the final report, so that it can serve as a stand-alone document. In addition, a response to comments on the white paper has not been provided, and should be prepared and submitted to the program office.

Response: Agreed.

Revision: The final report has been revised to incorporate the white paper.

3. **Front Material.** Provide a list of acronyms in front material following the list of appendices.

Response: Agreed.

Revision: A list of acronyms has been added to the final report.

4. **Executive Summary.** The project goals and objectives should be stated in the first paragraph of the Executive summary. A suggestion would be to move the second paragraph of the Executive Summary to the first and then reference Table E.1.

Response: Agreed.

Revision: Paragraph order has been revised so that project goals and objectives are stated in the first paragraph.

5. **Executive Summary (Table E2).** What do the two X's shown in the table cell for Longer Term Follow-up at Altus 418 Demonstration building represent? Please provide a footnote.

Response: The two X's were intended to represent two follow-up sampling events.

Revision: The table has been revised to improve the clarity.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

6. **Executive Summary: Summary of Demonstration Results.** The conclusions of the project need to be explicitly stated in the Executive Summary, and should include the following information:

   - A brief discussion on the regulatory drivers which require assessment of vapor intrusion.
   - The researcher's proposed "reliable and cost effective" method to better characterize vapor intrusion.
   - The advantages and disadvantages of the proposed vapor intrusion assessment approach relative to the current standard methods, including a discussion on the accuracy and precision of the proposed method compared to the current standard methods that are used to assess vapor intrusion.
   - The cost savings (or greater expense) that will be incurred to achieve the improved accuracy and precision resulting from the use of the proposed methodology.

Response: Agreed except regarding comparison to the typical investigation approach. Current regulatory guidance and standard industry practice do not currently provide a standard approach for the investigation of vapor intrusion. Therefore, the advantages of the recommended approach are discussed in terms of providing a consistent approach and reliable results. In addition, an evaluation of the impact of investigation program design on the accuracy of measured attenuation factors is provided in Section 4.6.4. Typical costs for the recommended investigation approach are presented, but the absence a current standard approach precludes a quantitative evaluation of cost savings.

Revision: The points above have been addressed as follows:

- A brief discussion on the regulatory drivers which require assessment of vapor intrusion has been added directly following the summary of the demonstration objectives (page E-2).
- Our proposed "reliable and cost effective" method is summarized on Pages E-9 to E-11.
- The advantages of the proposed vapor intrusion assessment approach relative are summarized on Page E-11.

7. **Executive Summary (Table E.3).** The existing summary of data quality performance (Table E.3) is out of place, and should follow the author's summary of the proposed method, a discussion of the proposed method's advantages and disadvantages relative to the current standard methods, and the cost implications to end users when using the proposed method.

Response: The summary of data quality performance is currently placed between the overview of the demonstration program and the summary of the demonstration findings. Since the demonstration findings represent the interpretation of the project data, it seems logical to discuss data quality before discussing these findings.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Revision: No changes to the organization of the executive summary have been made to address this comment.

8. **Executive Summary (Table E.4)**. For the performance criterion "Vapor Intrusion Impact", it is not certain what the phrase "clear indication" refers to in the column "Actual (post demo)". Could you please provide a more quantitative assessment? The presentation of Actual (Post Demo) results in this table do not match the description of findings (page 46) presented in Section 4.4.1 Vapor Intrusion Impacts. These should be aligned.

Response: The referenced finding on page 46 of the draft final report discusses the utility of indoor and ambient VOC measurements alone to identify the presence or absence of vapor intrusion impacts and does not include consideration of other site measurements. This finding indicates that these measurements were not sufficient to demonstrate an absence of vapor intrusion impact for Building 418 at Atlus AFB. The utility of the entire dataset (i.e., ambient, indoor, sub-slab VOC and radon analyses) to identify vapor intrusion impacts is discussed at the end of Section 4.4.1 under the heading "Overall Evaluation of Vapor Intrusion Impact". We feel that results described in Table E.4 are consistent with the findings presented in this section.

Revision: Actual (Post Demo) results text has been expanded to discuss both the vapor intrusion impact findings for the three demonstration buildings and to discuss likely the utility of the investigation program to identify the presence or absence of vapor intrusion impacts in other buildings.

9. **Executive Summary (Table E.4)**. For the performance criterion "Spatial and Temporal Variability in VOC Concentration", please provide a descriptive statement regarding the spatial and temporal variability observed during the study. It is not clear what the term "meaningful refers to (see comments regarding Section 4.4 and Appendix F).

Response: Agreed.

Revision: The actual results text has been revised to be more descriptive and specific.

10. **Executive Summary (Table E.4). For the performance criterion "Reliable Vapor Intrusion approach"**:

- Please insert the word "of" between "Identification" and "a" in the Expected Performance Metric column.
- The white paper has been reviewed with suggested major changes. The proposed approach needs to be provided in this document and referenced in the Executive Summary.

Response: Agreed.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Revision: The typographical error has been corrected and section references have been added to Table E-4.

11. **Executive Summary: Vapor Intrusion Impact.** What are the limitations and uncertainty in using radon as a tracer for characterizing vapor intrusion? Please provide some details on the results of this study to back up this statement.

Response: Agreed.

Revision: The discussion of radon in the executive summary has been moved to a separate subsection and the text has been expanded to provide additional detail and to discuss limitations.

12. **Executive Summary: Movement of VOCs across Key Interfaces.** Please justify how the evaluation of mass flux in shallow groundwater can provide a meaningful estimate of vapor intrusion given the large uncertainty in mass flux through soil gas and building foundations. The statements provided in this paragraph seem to be very contradictory to each other. Please provide some details on the results of this study to back up this statement.

Response: Agreed

Revision: The discussion has been expanded to explain why evaluation of mass flux in shallow groundwater may be useful despite the uncertainty and to clarify that validation of this screening approach is required.

13. **Executive Summary: Spatial and Temporal Viability in VOC Concentration.** Please provide some details on the results of this study to back up comparisons of short term and long term variability to measurement (duplicate) error and spatial variability. What was the RSD for the spatial and temporal variability in measured concentrations?

Response: Agreed.

Revision: The discussion of variability in the executive summary has been expanded to include a quantitative description of the analytical, sampling, spatial, and temporal variability observed in the demonstration data set.

14. **Executive Summary: Attenuation Factors.** Based on this study, are the EPA attenuation values overly conservative and protective? How conservative? Please provide some details on the results of this study to back up this statement.

Response: Based on the evaluation of three buildings conducted in this demonstration, it is not possible to make conclusions as to whether the USEPA default attenuation factors are overly conservative for general screening of vapor intrusion. The evaluation of USEPA default attenuation factors was intended

**APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2**

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

to be specific to the three buildings included in this demonstration. However, Section 4.6.4 has been added to the revised final report to evaluate the impact of variability on the attenuation factor database used by the USEPA to develop the default attenuation factors. This analysis indicates that the use of attenuation factors calculated using a single sub-slab measurement and a single indoor air measurement contributes to the development of overly conservative default (upper-bound) attenuation factors. However, Section 4.6.4 has been added to the revised final report to evaluate the impact of variability on the attenuation factor database used by the USEPA to develop the default attenuation factors. This analysis indicates that the use of attenuation factors calculated using a single sub-slab measurement and a single indoor air measurement contributes to the development of overly conservative default (upper-bound) attenuation factors.

Revision: The discussion has been revised to clarify that the USEPA defaults were conservative and protective for the three buildings evaluated. A comparison of measured attenuation factors to the USEPA defaults has been added.

15. **Executive Summary: Site Physical Characteristics.** How much less attenuation was observed in low permeability soils? What were the expectation and the observed results? Please provide some details on the results of this study to back up this statement.

Response: Agreed

Revision: This section of the executive summary has been revised to provide supporting details.

16. **Executive Summary: Summary of Project Deliverables.**

- The "white paper" needs to be finalized and modified per previous comments.
- Accessible Site Characterization Database. Please provide the database deliverable for review and comment.

Response: During our March project conference call, we agreed to defer revision of the white paper pending comments on the draft final report. A revised white paper and response to white paper comments is included with this submittal.

The database deliverable was provided to ESTCP with the draft final report, but was apparently not provided to the project reviewers.

Revision: None.

17. **Section 1.2: Objectives of the Demonstration.** Please define the "unacceptable" condition. What are the regulatory standards being used for this report?

Response: The term "unacceptable" was used in the introductory sentence of the paragraph. The remainder of the paragraph was intended to provide the explanation of the term "unacceptable". Because

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

the concentration of COCs in indoor air is a function of vapor intrusion, indoor sources, and ambient sources, vapor intrusion cannot be simply defined as an exceedance of regulatory standards, but, instead, requires a more complex definition. The regulatory standards used for evaluation data from each demonstration site are discussed in Section 4.4.1.

Vapor intrusion impacts at the demonstration sites have been evaluated in the context of both USEPA vapor intrusion guidance (Hill and Altus) and the site-specific regulatory standards established for the Hill AFB site.

Revision: The paragraph has been revised to further clarify the definition a vapor intrusion impact.

18. **Section 1.2: Objectives of the Demonstration (Project Results).** Please refer to the comments for project results in the Executive Summary.

Response: Addressed above.

Revision: Addressed above.

19. **Section 1.2: Objectives of the Demonstration (Project Results: Procedural Guidelines for Reliable Evaluation of Vapor Intrusion).** The white paper has been reviewed with suggested major changes. The proposed approach should be incorporated into the final report.

Response: The white paper has been revised to reflect comments on both the white paper and the final report. As requested, the proposed approach presented in the white paper has been included in the final report.

Revision: The proposed approach for cost-effective evaluation of vapor intrusion is presented in Section 4.6 of the final report.

20. **Section 1.3: Regulatory Drivers.** Please provide reference to RCRA and CERCLA requirements for assessing risk and corrective action. Also reference any DoD and OSHA requirements for maintaining safe work environments. A list of the states with regulatory requirements as of the time of this writing was provided in the Introduction (Section 1.1 Background), and should be reiterated in this section. Please cite the referenced regulations.

Response: Agreed

Revision: This section of the report has been revised to provide the requested references. In addition, new Appendix I provides a list of state and federal web sites on vapor intrusion.

21. **Section 1.4: Stakeholder/End-User Issues.** The information provided in this paragraph does not address end-user issues. Please provide a brief discussion on the value (advantages and disadvantages) to facility managers and risk managers when they use the proposed methodology.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

Response: Agreed.

Revision: Section 1.4 has been revised to focus more clearly on end user issues.

22. **Section 2.3: Factors Affecting Cost and Performance.** Please provide a discussion on the factors affecting the potential costs and performance for evaluating "vapor intrusion impacts" at a typical building using standard assessment methods and the proposed "reliable and cost effective" approach. Does the cost differential or performance of each approach change with the scale of the building size, foundation type, soils, depth to GW, contaminant etc.? When should an end-user use the proposed approach and when should they use the standard methods? Is a tiered strategy appropriate? It seems as if the text provided in this section should be part of Section 1.1 Introduction.

Response: As discussed in revised Section 1.4, there currently is no "standard" approach for the investigation of vapor intrusion. Recommended investigation approaches vary widely between guidance documents and often lack the detail needed to design a specific investigation program for a building, and, therefore, the actual investigation approaches also vary widely between parties. As a result, it is not possible to compare the cost of our recommended approach to the "standard approach" or to provide guidance on when to use which approach.

Although the performance factors listed by the reviewer are important, we feel that the available data from this demonstration do not support a more specific discussion of factors affecting cost and performance than has been provided.

Revision: None.

23. **Section 2.3: Factors Affecting Cost and Performance (Sampling and Analytical Variability).** Contamination of sample containers is a confounding factor related to cross contamination of samples and QA/QC procedures. Cross contamination of samples does not reflect true sample variability. The sources of sampling variability and analytical variability for indoor air and ambient air, for example, would include the very short term temporal variability resulting from shifting air currents while sampling and the low analytical precision resulting from measurements being made near the method detection limits.

Response: Agreed.

Revision: Text in Section 2.3 has been revised to reflect the comment.

24. **Section 2.3: Factors Affecting Cost and Performance (Sample Leaks).** This subsection should be renamed "Confounding Factors", and should discuss leaks, cross contamination, and other significant factors that are likely to contribute to poor precision and accuracy in Vapor Intrusion Investigations.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Response: Agreed.

Revision: Sample Leaks subsection has been revised as requested.

25. **Section 2.4: Advantages and Limitations of the Technology.** Please provide an explicit discussion of the advantages, disadvantages, and limitations of the proposed "reliable and cost effective" method in this section.

Response: As requested in Comment 21, a discussion of the advantages and disadvantages of the recommended investigation approach has been included in Section 1.4. Inclusion of the same discussion in Section 2.4 would be redundant.

Revision: None.

26. **Section 2.4: Advantages and Limitations of the Technology (Perception Problems).** The cost associated with perceived exposures, which may not be real, is the potential for toxic torts and third party liability. This might be good place to add a statement on the financial risk of incorrectly identifying whether vapor intrusion exists.

Response: Agreed.

Revision: A paragraph has been added to Section 2.4 to discuss the risks associated with misidentifying the presence or absence of a vapor intrusion impact. In addition, a sentence has been added to the "Perception Problem" paragraph to discuss liability.

27. **Section 3.1: Performance Objectives (Table 3.1).** Under the column titled "Actual Performance Objective Met?", could you please provide a reference to the section of the report where the data meeting the particular objective is provided?

Response: Agreed.

Revision: Section references added to Table 3.1

28. **Photo 3.5.1.3.** Please provide a more detailed description of what is being shown in the photo. What is the purpose of the masking tape? Why was a triangular hole cut in the flow as opposed to the more typical circular hole?

Response: A triangular cut in the carpet was used to minimize the visual evidence of the cut between sample events.

Revision: Additional details have been provided for the photo.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

29. **Table 3.5.6.1.** It is difficult to keep track of the sample collection activities at each residence at the Hill and Altus sites. It would be easier for the reader if Table 3.5.6.1 was modified to show the sampling activities for each residence separately.

Response: Agreed.

Revision: Table 3.5.6.1 has been modified to show collection activities at each test location.

30. **Section 3.5.7: Sampling Plan (Sample Point Purge Volumes).** References to data and its interpretation provided in Interim Reports should not be made in the final report. The final report is a stand alone document and must include the full data package for the project and its interpretation.

Response: Agreed

Revision: References to the interim reports have been removed and the full data interpretation is provided in the final report.

31. **Section 3.6: Selection of Analytical/Testing Methods.** The discussion describing the radon method accuracy is redundant to the information provided in the subsection Gas Sample Analysis on Page 30. Please revise text to eliminate the redundancy.

Response: Agreed.

Revision: Redundant text has been deleted from Section 3.6

32. **Table 4.1.1: Performance Criteria (Description).** Could you please provide a reference to the section of the report where the data are provided which support each individual Performance Criterion?

Response: Agreed.

Revision: Table 4.1.1 revised as requested.

33. **Table 4.2.1 (Vapor Intrusion Impact).** In the column "Actual (Post Demo)", was the indoor air clearly separated from ambient air intrusion in all cases? Didn't ambiguity exist for some estimates of vapor intrusion relative to the Expected Performance Metric? Please rephrase to reflect the statements on Page 45 for building 418 and the Findings (page 46) presented for section 4.4.1 Vapor Intrusion Impact.

Response: The discussion for Building 418 and the Finding referenced in the comment are specific to the use of only indoor and ambient measurements to identify vapor intrusion impacts. The performance criterion is for the use of ambient, indoor, and sub-slab VOC and radon measurements to identify vapor

**APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2**

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

intrusion impacts. As discussed in Section 4.4.1 of the final report, we believe that this full set of measurements allowed us to conclude that the demonstration buildings were free of vapor intrusion impacts even in cases where indoor and/or ambient COC concentrations were above established risk limits (e.g., TCE at Building 418). We believe that the Actual (Post Demo) finding is consistent with the discussion at the end of Section 4.4.1 under the heading "Overall Evaluation of Vapor Intrusion Impact".

Revision: The Actual (Post Demo) text has been revised as discussed in the response to Comment 8.

34. **Table 4.2.1 (Vapor Intrusion Impact).** In the column "Performance Confirmation Method", please see the above comment, and rephrase to clarify text.

Response: We are not sure how the above comment (Comment 33) related to the text in the "Performance Confirmation Method" column. We are also unsure whether it is appropriate to modify this text from what was presented in the original demonstration plan. We request additional guidance regarding this comment, if still applicable.

Revision: None

35. **Table 4.2.1 (Spatial and Temporal Variability in VOC Concentrations).** In the column "Actual (Post Demo)", what is meant by the word "meaningful"? Please be explicit or delete the word.

Response: Agreed.

Revision: Text revised (See also response to Comment 9).

36. **Table 4.2.1 (Attenuation Factors).** In the column "Actual (Post Demo)", please provide a range in reduced attenuation factors from default values.

Response: Agreed.

Revision: Comparison of measured attenuation factors to USEPA defaults provided.

37. **Table 4.2.1 (Site Physical Characteristics).** In the column "Actual (Post Demo)", the authors might wish to mention the importance of air pressure in buildings here.

Response: For residential buildings and many commercial buildings, building pressure is highly variable and often fluctuates between positive and negative relative to ambient or sub-slab pressure. As a result, we would not consider this to be a site physical characteristic analogous to soil permeability or depth to groundwater which generally vary over a relatively small range or not at all.

The importance of building pressure is discussed in Section 4.6.2 of the revised final report.

Revision: None

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

38. **Table 4.2.1 (Reliable Vapor Intrusion Investigation Approach).** The method needs to be presented in this report and the section referenced (i.e., the white paper should be incorporated into the Final Report).

Response: Agreed.

Revision: The recommended vapor intrusion investigation approach is presented in Section 4.6 of the revised final report.

39. **Section 4.3.2: Sampling Procedures and Field Instrumentation.** Please identify which samples failed to meet QA criteria due to sampling point leakage. Please describe the problem and how it was resolved.

Response: Agreed.

Revision: Discussion of sample point integrity moved to this section. New Table 4.3.2 and additional text added to Section 4.3.2 to identify the samples impacted and the corrective measures implemented.

40. **Section 4.3.3: Precision Assessment (Analytical Detection Limits).** Didn't the DQO change following the first sampling event, forcing a shift to the TO15 low resolution method on some samples? A brief statement on the problem encountered and the resolution should be provided here so that the reader doesn't make the same mistake in the future.

Response: Agreed

Revision: A paragraph has been added to discuss this issue.

41. **Section 4.3.3: Precision Assessment (Laboratory Precision).** An explicit and brief statement on the Summa canister cross-contamination issue should be mentioned and the resolution to the problem (100% certification) should be provided here so that the reader doesn't make the same mistake in the future.

Response: Agreed.

Revision: A paragraph has been added to discuss this issue.

42. **Section 4.3.4: Accuracy Assessment (Sample Point Integrity).** It would make more sense for the discussion on Sample Point Integrity to be in Section 4.3.2 (Sampling Procedures and Field Instrumentation).

Response: Agreed.

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Revision: The text discussion on sample point integrity has been moved to Section 4.3.2.

43. **Section 4.4.1: Vapor Intrusion Impact.** The analysis of the potential for vapor intrusion should include, where possible, the use of TCE to PCE ratios and TCE to radon (and PCE/radon) ratios for individual soil gas, sub-slab, ambient and indoor air. These ratios will provide additional weight-of-evidence to support a determination of whether the vapor intrusion pathway is Soil gas->Subslab->Indoor Air or Ambient->Subslab->Indoor Air.

Response: Agreed.

Revision: New Subsection "Evaluation of VOC to Radon Ratios" and new Table 4.4.1.6 added to Section 4.4.1.

44. **Section 4.4.1: Vapor Intrusion Impact.** Have the multiple lines of evidence been weighted based on degree of certainty? Does an indirect method (radon intrusion) carry the same weight as direct measurements of indoor air vs. ambient air? Is the ratio of TCE/Radon in soil gas, subslab, and indoor air consistent? Please provide details on the weight-of-evidence approach used. A table listing the lines of evidence, the pros and cons of each line and a subjective weighting factor might be useful as part of the "reliable" method for assessing vapor intrusion.

Response: Agreed. However, as discussed in the revised text, the weighting varies from event to event depending on the results obtained. For example, VOC analyses may be most important when VOCs are absent in sub-slab and below screening levels in indoor air. However, radon analyses will be more important when VOCs are present in both sub-slab and indoor air samples and VOC/radon ratios suggest a contribution from indoor or ambient sources.

Revision: Additional discussion has been added to the subsection "Overall Evaluation of Vapor Intrusion Impact" and new Table 4.4.1.7, Analyses Used to Evaluate Vapor Intrusion Impacts, has been added.

45. **Section 4.4.1: Vapor Intrusion Impact.** Has the use of different screening criteria used to define vapor intrusion impact affected the scientific analysis? Why would the residential indoor air background be different from one base to another?

Response: The selection of the specific indoor air screening concentration would not change the data analysis methods used, and would not change the conclusion regarding the presence or absence of a vapor intrusion impact above regulatory standards.

The USEPA 2002 indoor air screening concentration for TCE is 0.0022 - 0.22 ug/m^3 and for PCE is 0.81 to 81 ug/m^3 based on a 10^{-6} to 10^{-4} risk range. The indoor air action level for TCE at Hill AFB is 2.3 ug/m^3. No site-specific indoor air action levels have been established for Altus AFB.

At Altus AFB, the estimated indoor air concentration of PCE and TCE due to vapor intrusion (See Table 4.4.1.5) was less than the USEPA 10^{-6} risk level during all sampling events. At Hill AFB, the estimated

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

indoor air concentration of TCE due to vapor intrusion was less than the Hill AFB action level during all sampling events and less than the USEPA 10^{-6} risk level for three of four evaluations. For Residence #1 during March 2006, the estimated indoor air concentration of TCE due to vapor intrusion was 0.082 ug/m^3, a value between the USEPA 10^{-5} and 10^{-6} risk levels. However, the USEPA screening level for TCE is based on a proposed TCE cancer slope factor that has not been officially adopted by the USEPA and is disputed by the DoD. In the USEPA 2001 VI guidance, the indoor air screening level for TCE was 0.59 ug/m^3 for the 10^{-6} risk level based on the older TCE slope factor.

In summary, all buildings show an absence of vapor intrusion impacts for all sample events regardless of the screening criteria used with the exception of Hill AFB Residence # 1 during the March 2006 sampling event. For this residence, a vapor intrusion impact is indicated only if the proposed TCE slope factor and the 10^{-6} risk level are both applied. If either the older TCE slope factor or a 10^{-5} risk level are applied then no vapor intrusion impact is indicated.

Ambient air background is likely to vary from base to base depending on the local and regional VOC emissions. Indoor VOC background will vary from building to building depending on the presence or absence of indoor sources in the building.

Revision: None

46. **Section 4.4.1: Vapor Intrusion Impact (Building 418, Altus AFB).** Could the difference between the ambient and indoor air be the result of analytical variability? Could you please discuss how the December 2006 "difference" between indoor and ambient air TCE and PCE concentrations compare to the range of differences observed between duplicate analyses?

Response: Based on a two-sample t-test with assumed equal variance, none of the differences between ambient and indoor TCE and PCE concentrations for any of the sampling events at any of the buildings are statistically significant at the 95% confidence level. However, the differences between indoor and ambient PCE and TCE are significant at the 90% confidence level for the December 2006 sampling event (see Section 4.4.1, Measured Indoor VOC Concentration, Building 414, Altus AFB). In addition, the TCE and PCE concentration in all three indoor samples was higher than the concentration in the highest ambient sample. This indicates that the observed difference between TCE and PCE in indoor and ambient air during this sampling event is most likely real and not due to analytical variability.

Over the course of the demonstration, the variability between field duplicate samples for indoor and ambient air was low with 8 of 13 duplicate PCE and TCE measurements having an RPD of less than 10% with only one duplicate measurement having a RPD of greater than 100% (i.e., >3x difference). This level of agreement is impressive given the very low concentrations of PCE and TCE in indoor and ambient air (i.e., almost always less than 1 ug/m^3) such that very small absolute differences in concentration yield a large RPD.

Revision: None.

47. **Table 4.4.1.1 (Footnote).** Please change "on-detect" to non-detect".

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Response: Agreed.

Revision: Typographical error corrected.

48. **Section 4.4.1: Vapor Intrusion Impact (Residence #2, Hill AFB).** If the goal of the t-test was to evaluate whether indoor air concentration exceeds ambient air, then this test should be conducted as a one-tailed test.

Response: The goal of the analysis was to test whether the concentrations were significantly different (i.e., either above or below). The sentence referenced in the comment indicates that a significant difference was found and indicates the direction of the observed difference.

Given that either indoor sources or vapor intrusion would result in indoor VOC concentrations above ambient concentrations, and no obvious mechanism would result in indoor VOC concentrations less than ambient concentrations, it would be reasonable to conduct a one-sided test of the difference between indoor and ambient concentration. However, a two-sided test has the advantage of not depending on any specific conceptual model of the expected differences in concentration and is also less likely to yield a false positive indication of statistical significance.

Revision: None.

49. **Section 4.4.1: Vapor Intrusion Impact (Evaluation of Uncertainty).** The evaluation of uncertainty could be expanded, which would provide much more useful information to the end-users of the research. For example, environmental data like this are typically log normally distributed. The variance around the geometric mean is usually better expressed as a factor relative to the mean. A better estimate of uncertainty for the concentration of volatile organics in ambient, indoor and subslab air would be to conduct an analysis of variance (ANOVA) of the log transformed data using a random effects statistical model. One potential model would include chemical type (PCE and TCE) and source of air (indoor, subslab, and ambient) as the fixed effects. The site (Altus or Hill), sample location within site, and sample date could then be treated as random effects. Using this approach would allow for direct comparison of spatial and temporal variance relative to the model error (sampling and analytical variance). The regression analysis would also permit calculation of confidence intervals for mean values.

Response: Although we agree that an ANOVA would provide a more meaningful evaluation of variability in a larger data set, the total data set generated for this demonstration is not of sufficient size to support a meaningful analysis using an ANOVA model. In an attempt to be response to the reviewer comment, we conducted exploratory analyses using an ANOVA model and encountered the following difficulties:

- The overall dataset is small relative to the number of variables proposed by the reviewer, leading to a small number of degrees of freedom. This results in a model that is highly sensitive to

APPENDIX J.1: RESPONSE TO REVIEWER'S COMMENTS
FINAL REPORT VERSION 2

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

factors that are not actually meaningful for understanding variability in VOC concentrations at vapor intrusion sites.

- Approximately 40% of the PCE and TCE analytical results were non-detect but the prevalence of these non-detect results differs between constituents and sites. For example, PCE was rarely detected at the Hill AFB residences. In addition, the detection limits for indoor and ambient air samples were much higher for the first Altus sampling event than for all subsequent sampling events. Due to the high prevalence of non-detect results, the use of proxy values for non-detect results does not provide an accurate evaluation of the sources of variability in areas where the VOCs are actually present. Elimination of the non-detect results from the data set results in a small and unbalanced data set not suitable for analysis using an ANOVA model.

Based on these difficulties, we have not used an ANOVA model to describe the sources of variability in the demonstration data set.

Revision: None

50. **Section 4.4.1: Vapor Intrusion Impact (Evaluation of Uncertainty).** How does the estimate of variance described for compare to the variance associated with MS/MSD, sample duplicates and the recovery of surrogates?

Response: As discussed in revised Section 4.4.3, laboratory duplicates and surrogate recoveries indicate very low analytical variability. The TO-15 method does not include MS/MSD analyses.

Revision: A discussion of analytical and sampling variability has been added to Section 4.4.3.

51. **Section 4.4.1: Vapor Intrusion Impact (Estimated Indoor VOC Concentrations Attributable to Vapor Intrusion).** There are some suggested rewordings for this section. Please consider rewording the first sentence from "....it is unlikely that all of the .... " to "....it is possible that none of the...." Also if the word "likely" is changed to "potential" in the next and last sentence of the paragraph, although trivial, may have a big impact on the meaning.

Response: Agreed.

Revision: As recommended.

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

1. **General Comments.** Because of the nature of the document, it might be better to entitle it as "lessons learned" or "recommendations" rather than a recommended approach.

Response: Agreed.

Revision: Title changed to "Recommendations for the Investigation of Vapor Intrusion".

2. **General Comments.** In reading the document, it seems that the context should be framed in terms of potential human health risk, not "vapor intrusion impacts". The term "vapor intrusion impacts" is vague and leaves the reader with a very limited understanding of the purpose for the work. The introduction would be clearer if the authors introduced the report with the current risk model used by the EPA to estimate the exposure and potential for toxic effects (chronic and carcinogenic). By doing this, the reader would have the context for understanding the significance of the uncertainty in our understanding of the vapor intrusion exposure pathway.

Response: We disagree that it would be more helpful to evaluate vapor intrusion in the context of potential human health risk. We believe that the most important question for the end user is "Is a response action required", which is a regulatory question. We agree that most regulatory frameworks are based on potential human risk, however, these frameworks may also consider background, analytical detection limits, and other non-risk factors. In our revised final report and white paper, we have attempted to clearly define the term "vapor intrusion impact" in the context of regulatory requirements to implement a response action.

Revision: Meaning of "vapor intrusion impact" defined in White Paper (Section 1.2)

3. **General Comments.** The analysis of spatial, temporal, and analytical variability should be reviewed and adjusted (see specific comments below).

Response: The project Final Report (written after the first draft of the White Paper) provides a comprehensive evaluation of variability. We have decided to remove the section on variability from the White Paper and to discuss variability only in the context of it's impact on the recommended investigation program. Specific comments concerning the discussion of variability in the White Paper have been addressed in the revised Final Report (see Response to Comments 12 to 29, below)

Revision: Section 3.0 removed from the revised White Paper.

4. **Section 1.1 (Field Investigation)(Page 2, Line 9).** The guidance does not provide recommendations for addressing the spatial, temporal, and analytical uncertainty in the assessment. This should be included in a revision.

Response: Agreed.

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

Revision: The referenced sentence has been revised to clarify that the USEPA guidance does not provide recommendations for addressing spatial or temporal variability.

5. **Section 1.2 (Identification of Indoor Air Impacts)(Page 3, Line 4).** This statement should be tempered to reflect the trade off between accuracy, time available for reaching a decision, and cost, as the most accurate data set may not be feasible to collect.

Response: Agreed.

Revision: Text revised to reflect consideration of cost, time, and accuracy.

6. **Section 2.1.1 (Additional Research)(Page 4, Line 24).** It seems that the previous sentence indicates that additional research is not required. Could you please justify this conclusion?

Response: The discussion of findings to date indicates that, at the sites evaluated, monitoring wells with longer screens did not provide an accurate evaluation of VOC concentrations at the top of the water table, as is needed for the evaluation of vapor intrusion. The discussion of additional research was intended to indicate that the findings to date may not be applicable to all sites. However, all of the sections discussing additional research needs have been removed in order to focus the White Paper more clearly on the recommendations for investigation of vapor intrusion.

Revision: Sections addressing additional research have been removed.

7. **Section 2.2: Soil Gas Samples (Page 4, Line 32).** The term “point(s)” is used approximately 20 times in the next two paragraphs. In some cases, the term “points” refers to locations and in other cases, it refers to equipment. This section should be edited so that the reader can easily follow the line of thought.

Response: In all cases the term “point” is intended to be interchangeable with “location” to indicate the location of soil gas sample collection.

Revision: Text revised to define “sample point” and to distinguish between sample point and associated lines and hardware.

8. **Section 2.2.1: Placement of Sample Points (Page 4, Line 36).** Measuring soil gas concentrations near the source provides almost no information regarding the exposure pathway. It only provides input data for an exposure model that provides poor predictions of subslab gas concentrations and indoor air quality. Therefore, it is not clear as to what information this measurement will provide. Please comment.

Response: We agree that the presence of VOCs in soil gas near the source at concentrations above conservative screening concentrations provides little information regarding the potential for vapor

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

intrusion impacts. However, we believe that an absence of VOCs in soil gas close to the source can provide a reliable indication that the pathway is incomplete. For example, the absence of VOCs in deep soil gas above a contaminated water-bearing unit indicates an absence of transport from groundwater to soil gas. This may be due to the presence of a clean water layer at the top of the water-bearing unit or the presence of a low permeability confining layer at the top of the water-bearing unit.

As discussed in the White Paper, many vapor intrusion guidance documents recommend a step-wise approach for the evaluation of the vapor intrusion pathway that progresses from source evaluation to receptor evaluation. We feel that this conceptual framework is appropriate and provide recommendations consistent with this framework.

Revision: None.

9. **Section 2.2.1: Placement of Sample Points (Page 4, Line 41).** The information presented in this section appears to contradict that provided in Section 3.3. Please provide a rationale for these comments, or revise the text accordingly.

Response: We don't see a contradiction between these two sections. In Section 2.2.1 we recommend that sample points to evaluate migration from the source to soil gas should be placed close to the source while sample points to evaluate migration from soil gas to the receptor should be placed close to the receptor. In Section 3.3, we address an issue specific to the placement of sample points close to the receptor.

Revision: Parentheticals have been added to Section 2.2.1 to clarify the difference between pathway screening a direct evaluation of vapor intrusion impacts.

10. **Section 2.2.2 (Study Findings)(Page 5, Line 12).** Earlier reports from this project discussed the leakage of soil gas sampling equipment. This should be discussed in this section, along with recommendations regarding equipment, sampling procedures and QA/QC activities necessary to obtain reliable measurements.

Response: Agreed

Revision: New Section 2.2.3 added to address use of leak tracers.

11. **Section 3.0: Variability (Page 5, Line 35).** This section seems to belong in section 2.2 (Soil Gas Samples).

Response: The project Final Report (written after the first draft of the White Paper) provides a comprehensive evaluation of variability. We have decided to remove the section on variability from the White Paper and to discuss variability only in the context of it's impact on the recommended investigation program. Specific comments concerning the discussion of variability in the White Paper have been addressed in the revised Final Report (see Response to Comments 12 to 29, below)

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Revision: Section 3.0 removed from the revised White Paper.

12. **Section 3.0: Variability (Page 5, Line 39).** Duplicate variability is mentioned here. Does this mean analytical variability? There should be a subsection in the report which defines what is meant by this term.

Response: Section 4.4.3 of the final report provides a discussion of analytical and sample variability that addresses this comment.

13. **Section 3.1: Spatial Variability.** This section provides a weak analysis of the spatial variability in the data set. It is suggested in the text that it might be important, and then recommended that additional research be performed. The recommendations are not clear about how to manage spatial variability nor how to estimate the number of samples required to meet the data quality objectives. The data quality objectives to help manage the spatial variability should be reported. In addition, what are the factors which appear to be related to the spatial variance?

Response: A comprehensive discussion of spatial variability is provided in Section 4.4.3 of the final report.

14. **Section 3.1: Spatial Variability (Page 6, Line 13).** Please provide a reference for the Endicott, NY results.

Response: Agreed.

Revision: In the Final Report, reference added to unpublished work by Bill Wertz, NYDEC, 2006.

15. **Section 3.1 (Recommendation)(Page 6, Line 15).** See comment for Page 4 Line 36 above.

Response: See response above

16. **Section 3.1 (Recommendation)(Page 6, Line 17).** In Section 3.3, collecting subslab gas samples is recommended. However, here samples in close proximity to the potentially impacted building are recommended. Could you please clarify there recommendations and make the appropriate changes in the text?

Response: Referenced text removed from revised White Paper.

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

17. **Section 3.1 (Recommendation)(Page 6, Line 19).** It is mentioned that site specific factors should be used to estimate the number of samples. What site specific factors and data are needed to estimate the number of samples required?

Response: Section 4.4.3 of the Final Report discusses statistical methods to estimate sample numbers based on observed or expected variability.

18. **Section 3.1 (Recommendation)(Page 6, Line 20).** It is stated that “Spatial variability is likely to be higher at sites with predominately fine-grain soils or interbedded layers of fine and coarse grain soils”. Is this statement based on the results of this research? If so, it should be moved to the findings section.

Response: Referenced text removed from revised White Paper.

19. **Section 3.1 (Additional Research)(Page 6, Line 23).** It is stated that “Small-scale variations in soil permeability and moisture content likely contribute to high spatial variability in soil gas COC concentrations”. Please provide the basis for this statement.

Response: Referenced text removed from revised White Paper.

20. **Section 3.2: Temporal Variability (Page 6, Line 32).** The sentence “Higher temporal variability requires a larger number of sampling events while a larger time-scale for variation (i.e., annual vs. daily) requires that the sample events be spaced over a longer time interval” is not clear. Could you please rephrase this sentence?

Response: Referenced text removed from revised White Paper.

21. **Section 3.2 (Study Findings)(Page 6, Line 39).** An RPD of 100% seems like a big difference. You might want to consider presenting the results on a log scale. Was the spatial variability in one direction or was it increasing, decreasing or random?

Response: Referenced text removed from revised White Paper. Issue addressed in Section 4.4.3 of the Final Report.

22. **Section 3.2 (Recommendation)(Page 7, Line 5).** It is not clear what the authors wish to state in this recommendation section. For example, what is the basis for this statement given that the temporal variance can exceed 100-fold, what is the meaning of a marginal case, what is a small number, what is considered adequate, what statistics should be used to estimate the expected variance, and over what period of time? Shouldn’t the analysis of temporal variability be discussed in relationship to the risk assessment model?

**APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION**

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

Response: Referenced text removed from revised White Paper.

23. **Section 3.2 (Additional Research)(Page 7, Line 12).** It is mentioned that consistency of results between researchers is the basis for this statement. Who are the researchers? Please provide references.

Response: Referenced text removed from revised White Paper.

24. **Section 3.3: Below Vs. Adjacent to Building (Page 7, Line 16).** A direct evaluation of risk resulting from vapor intrusion is determined by measuring indoor air quality. Subsurface soil gas concentrations are an indirect method to arrive at this information. Please revise the text accordingly.

Response: Referenced text removed from revised White Paper.

25. **Section 3.3: Below Vs. Adjacent to Building (Page 7, Line 18).** The statement "However, it is unclear whether soil gas samples obtained adjacent to a target building are representative of VOC concentrations below the building foundation" requires further explanation.

Response: Referenced text removed from revised White Paper.

26. **Section 3.3 (Study Findings)(Page 7, Line 26).** It is not clear what this statement means. Could you please describe how these results compare to the spatial and temporal variability described above? In addition, do the data fall within the analytical variance expected for duplicates and the spatial variability in multiple sub slab measurements?

Response: Referenced text removed from revised White Paper.

27. **Section 3.3 (Recommendation)(Page 7, Line 30).** Please modify earlier statements on soil gas vapor monitoring to reflect this recommendation.

Response: Referenced text removed from revised White Paper.

28. **Section 3.3 (Additional Research)(Page 7, Line 33).** It is not clear what is meant by "general" spatial variability. Please explain why the existing data is not sufficient to ascertain spatial variability.

Response: Referenced text removed from revised White Paper.

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

29. **Section 3.3 (Additional Research)(Page 7, Line 36).** The soil gas exchange measurement is a good idea; however, the results will be highly dependent upon changes in barometric pressure and the flux of surface air into soil. This will introduce another level of variability that will need to be accounted for.

Response: Referenced text removed from revised White Paper.

30. **Section 4.0: Field Investigation Approach.** This section should be rewritten so that subsections are presented in a consistent fashion, and each subsection should have explicit recommendations. Any project findings and results should be moved to the previous sections.

Response: Agreed.

Revision: Section 3 (formerly Section 4) has been revised to provide a specific recommended approach of the building-specific evaluation of vapor intrusion.

31. **Section 4.0: Field Investigation Approach (Page 8, Line 6).** Does "field investigation" include the direct measurement of indoor air quality? A discussion should be included as to when and how should a survey of indoor air quality should be performed

Response: We believe that the initial screening of buildings can appropriately be conducted based on either indoor air sampling or below-foundation gas sampling.

Revision: Section 3.1 (formerly Section 4.1) has been revised to recommend initial building screening based on either indoor air or below-foundation gas samples..

32. **Section 4.0: Field Investigation Approach (Page 8, Line 9).** The recommendations for cost-effective field investigation do not include any estimated costs. Could you please provide them in this section?

Response: Agreed

Revision: Cost information is provided in Section 3.3 of the revised White Paper.

33. **Section 4.1: Receptor Screening (Page 8, Line 11).** It is not clear how well the screening results compared to measured indoor air concentrations. Could you please report this comparison in a subsection of the Findings section?

Response: This analysis is provided in Section 4.4.1 of the Final Report

Revision: None

APPENDIX J.2: RESPONSE TO REVIEWERS COMMENTS
WHITE PAPER: RECOMMENDATIONS FOR THE INVESTIGATION OF VAPOR INTRUSION

DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES
ESTCP Project No. CU-0423

34. **Section 4.1: Receptor Screening (Page 8, Line 12).** This sentence seems unnecessary, since all vapor intrusion investigations are building specific.

Response: Agreed.

Revision: Wording has been revised.

35. **Section 4.1: (Recommendation)(Page 8, Line 23).** This recommendation does not take into account temporal or spatial variability. It would be nice to include language in the recommendation that alludes to the potential for changing site conditions.

Response: Agreed.

Revision: Revised text discusses the potential need for multiple sampling event to characterize temporal variability and addresses the impact of spatial variability on the design of the sampling program.

36. **Section 4.2: Receptor Evaluation.** The titles of both Subsections 4.1 (Receptor Screening) and 4.2 (Receptor Evaluation) are somewhat misleading, at least in terms of a risk assessment paradigm. It might be appropriate to rename these subsections.

Response: We feel that buildings are appropriately characterized as receptors for the purpose of vapor intrusion risk assessment, however, the sections have been renamed to improve clarity.

Revision: Sections renamed.

APPENDIX J.3: RESPONSE TO COMMENTS
FINAL REPORT VERSION 2, DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

1. This report would benefit from a discussion on how to interpret vapor intrusion data that are over or under regulatory screening values or the various metrics. For example, when the measurement of the concentration of a chemical in indoor air, based on one analysis, is over regulatory screening values by 10%, 20%, or 50%, what is the probability that collection of additional measurements will provide an average concentration of indoor air contaminants that is less than the screening value? Providing some context on the spatial and temporal variability in Section 4.6.2 would be useful.

   Also, a number of specific comments on the White Paper appear to apply as well to the Final Report and the authors should modify the final report as necessary so that it is consistent with the final revision of the White Paper (see Comments on the White Paper Recommended Approach for the Investigation of Vapor Intrusion Impacts (Version 2)).

Response: Due to the potential confounding impact of indoor sources and numerous other site-specific factors, we do not feel that it is possible to provide a quantitative discussion of the probability that additional monitoring will change the initial indication of the presence or absence of a vapor intrusion impact. However, we have added a qualitative discussion to Section 4.2.6 of the impact of variability on the evaluation of vapor intrusion.

Revision: Discussion added to Section 4.2.6. Where appropriate, the responses to comments on the White paper have also been incorporated into the Final Report.

2. **Evaluation of VOC to Radon Ratios (Page 55, Second Paragraph).** The PCE/Radon ratios are consistent for all three media (soil gas, indoor air, and ambient air) for Building 418 at Altus AFB. The authors make the claim that this indicates that the subsurface is the primary source of PCE. Is it plausible that the ambient air could be the source of PCE? If the absolute concentrations are the same in soil gas, indoor air, and ambient air then one would assume that ambient air is the source. If the soil gas concentrations are higher than the ambient air then the alternative is likely. The additional information on absolute concentrations should be included in the discussion.

Response: As shown in Table 4.4.1.4 (two pages before this section), PCE concentrations in soil gas are much higher than in indoor or ambient air, clearly indicating ambient air is not a source of PCE in soil gas. A sequential reader of the report should recall these data, however, this section has been revised to clarify the discussion.

Revision: Section on evaluation of VOC to Radon ratios revised to clarify that PCE concentrations in soil gas at Building 418 were much higher than PCE concentrations in indoor or ambient air.

3. **Hill AFB Residence #1 Building Depressurization Study (Page 56, Second Paragraph).** Can the authors provide an explanation for the increase in the TCE/Radon ratio in ambient air between the pre-depressurization vs. during depressurization sampling for Residence #1 at Hill AFB? It seems that the increase in TCE/Radon ratios for soil gas and indoor air during the depressurization study (compared to pre-depressurization) suggests that a significant amount of

APPENDIX J.3: RESPONSE TO COMMENTS
FINAL REPORT VERSION 2, DETAILED INVESTIGATION OF VAPOR INTRUSION PROCESSES

ESTCP Project No. CU-0423

> the TCE present in soil gas and indoor air would result from an ambient air source. Please comment and revise the conclusions in the text accordingly.

Response: The ambient radon concentration was significantly lower during the depressurization study compared to pre-depressurization (0.010 pCi/L vs. 0.095 pCi/L). This difference may be attributable to a wet snowfall of about 2 inches that fell overnight between the baseline and depressurization measurements of ambient radon. This snowfall may have temporarily reduced the migration of radon from soil gas to ambient air. This decrease in ambient radon is responsible for the increase in the ambient TCE/radon ratio. Under depressurization conditions, both the indoor and the soil gas TCE concentrations were higher than the ambient TCE concentration indicating that ambient TCE was not a significant source to either indoor air or soil gas.

Revision: None.